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An Oceanography-Based Anticipatory Approach to Monitoring Fisheries and Fishery Resource Impacts From Offshore Wind Farms: A Perspective From the Mid-Atlantic Bight, USA

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ABSTRACT

The Middle Atlantic Bight (MAB) of the eastern US differs from other offshore wind (OSW) development sites due to a unique seasonal oceanographic stratification regime. Fisheries there target migratory finfish and sedentary shellfish, the productivity and distribution of which are driven by oceanography with dynamic mesoscale features that can encompass one or more OSW leases. The regulatory environment allows competition among universities and private companies in designing and executing innovative Fisheries Monitoring Plans (FMPs) under federal guidelines but has hindered a comprehensive plan that considers all the wind farms proposed for the MAB under shifting timelines. Different FMPs reflect that OSW development itself is not unified, but FMPs could integrate and share data. Here we present a perspective on an FMP developed as several surveys implementing Before-After-Control-Impact (BACI) and Before-After-Gradient (BAG) designs to meet the challenges of this environment. These anticipate built structures and other nonaligned leases in an "oceanography based" approach. This plan roots analysis in an ecological understanding of the MAB even if methods require resource-by-resource survey. It is also novel in planning around potential sampling impacts by project development, and in anticipating concerns that multiple, independent, or loosely unified campaigns would otherwise bring. It merges extractive and nonextractive methods to support development of survey strategies that anticipate structural hindrance, limit cumulative impacts, and protect sensitive resources. Finally, it fully integrates commercial fisher participation in the design and execution to utilize the sector's extensive knowledge, capable vessels, potential displaced effort, and community trust building in survey results.

1 | Introduction

Offshore wind (OSW) power developments (i.e., windfarms) are becoming increasingly important to meeting environmental, economic, and energy system objectives worldwide. OSW projects are in their infancy in the United States, with the first commercial OSW farm, Block Island Wind Farm (five turbines, 30 MW) operational in 2016 (Ørsted 2022). Currently, the Coastal Virginia Offshore Wind Pilot Project (two turbines, 12 MW, operational in 2020) (BOEM 2020), South Fork Wind (12 turbines, 132 MW, operational in 2024), and Vinyard Wind (operating 17 of a planned 62 in 2025) produce power while other projects have completed installation of some turbines. Although currently paused by federal Executive Order (White House 2025), cumulative goals set by State governments would put the United States ahead of the current global capacity of 72 gigawatts (Statista 2024). The extent of these plans drives a need to understand OSW impacts on fisheries resources and fishing activities (e.g., Szostek et al. 2025) in the United States, including comparison to other OSW developments worldwide.

The initial focus of OSW development for the United States is on the east coast and especially the Middle-Atlantic-Bight (MAB, between Cape Cod, Massachusetts, and Cape Hatteras, North Carolina, Figure 1). The geomorphology of the MAB is characterized by a broad, shallow, continental shelf primarily comprised of unconsolidated sediments. This water depth and sediment type lend themselves to the same type of fixed-bottom turbine foundations that have been operational since the mid-1990s in locations including the North Sea, English Channel, Bristol Sea, and Irish Sea. However, despite these geomorphological similarities, the MAB is characterized by a uniquely stratified and seasonal oceanographic regime (Miles et al. 2021), different species with varying life histories, and a different regulatory environment, all of which preclude immediate application of some lessons learned from European and Asian windfarms to the MAB in terms of understanding and monitoring OSW development effects on fisheries and fisheries resources.

A downstream effect of the regulatory environment is the inclusion of robust competition in executing required impact studies that promote local, regional, academic, and private sector involvement. While competition frequently leads to innovation, to date it has also promoted disjointed monitoring approaches rather than a coordinated and comprehensive plan among windfarms (but see ROSA 2021 regarding efforts to unify these). For example, FMPs of more offshore projects are focused on scallops and highly migratory pelagic fish to the exclusion of clams and benthic fish because of the difference in habitat value to these species with increasing depth. Guidelines are provided by a Federal entity, the Bureau of Ocean Energy Management (BOEM). BOEM considers conflicts in public use and access to the same areas when leasing submerged public lands to OSW energy developers, but coexistence and spatial overlaps of ocean users will inevitably cause conflicts with fisheries, aquaculture, wildlife, shipping, and OSW development (Schupp et al. 2019; Szostek et al. 2025). While BOEM can stipulate conditions of the lease, including investment in fishery resource monitoring, it does not regulate fisheries, which is the responsibility of the National Oceanic and Atmospheric Administration (NOAA) and the National Marine Fisheries Service (NMFS). For example, fishing access to wind farms will not be denied in the United States, while at least mobile gear is restricted in OWF in Europe (European Commission 2020; Bonsu et al. 2024). Additionally, attempts to address the concerns of one of these regulatory agencies may conflict with those of another. For example, a mandate for robust assessment surveys may conflict with restrictions placed on surveys by agencies concerned with protecting certain species. An Incidental Take Permit or Biological Opinion (BiOp) must be obtained prior to survey given that interactions with Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) or sea turtles are possible. Furthermore, the BiOp or permit conditions may limit the total number of gear sets per year especially in light of the potential for cumulative effects of numerous, independently contracted surveys for each Construction and Operation Plan (COP). Vessel speed restrictions and a requirement for onboard marine mammal observers have, in our own experience, hindered survey scope or efficiency, science crew size, and flexibility in timing relative to sea conditions. Challenges such as these introduce new dimensions to the development of fisheries monitoring plans (FMPs) in the United States.

This article documents the development of a coordinated and comprehensive FMP based on experiences from two such plans (Ørsted Ocean Wind 1 OCS-A 0498 and Atlantic Shores Offshore Wind COP South OCS-A 0499 and OCS-A 0570) and makes recommendations for effective, coordinated FMPs at other wind farms. The plan is novel in several ways. It is rooted in an oceanography-based ecological understanding of the MAB. It relies on commercial fishers and their vessels for sampling. It is proactive in its anticipation of sampling designs that would ultimately be impacted by project development, and in anticipating concerns that would otherwise result from multiple, independent, or loosely unified efforts. Finally, it merges traditional extractive survey methods with nonextractive survey methods to support the development of survey strategies that limit impacts, protect sensitive resources, and provide alternatives for future scenarios where traditional sampling may be excluded.

2 | Approach

The model FMP is based on one that was initiated as an interdisciplinary approach and incorporates recommendations from the regional scientific community (Brodie et al. 2021; ROSA 2021). It both recognizes the need for sampling before, during, and after construction within and away from the impacted site (Methratta 2021) and the need to measure the effects of spatial measurement scale. Change to hydrography is the first-order driver of changes to habitat use. Storms and hurricanes, currents from neighboring regions, river discharge, stratification and sea surface fronts, and atmospheric heating and cooling will naturally change animal distributions daily, seasonally, and yearly. Harvest can also change marine animal populations. While labeled as a "monitoring plan," this FMP is structured on the basis of challenging several core null hypotheses based on five ecological mechanisms. Broadly, these mechanisms are 1) changes that deviate from oceanographic dynamics in the rate and strength of physical habitat disturbance that they produce; 2) changes to spatial habitat heterogeneity; 3) changes to fishing practice and effort; 4) changes to foraging practices; and 5)

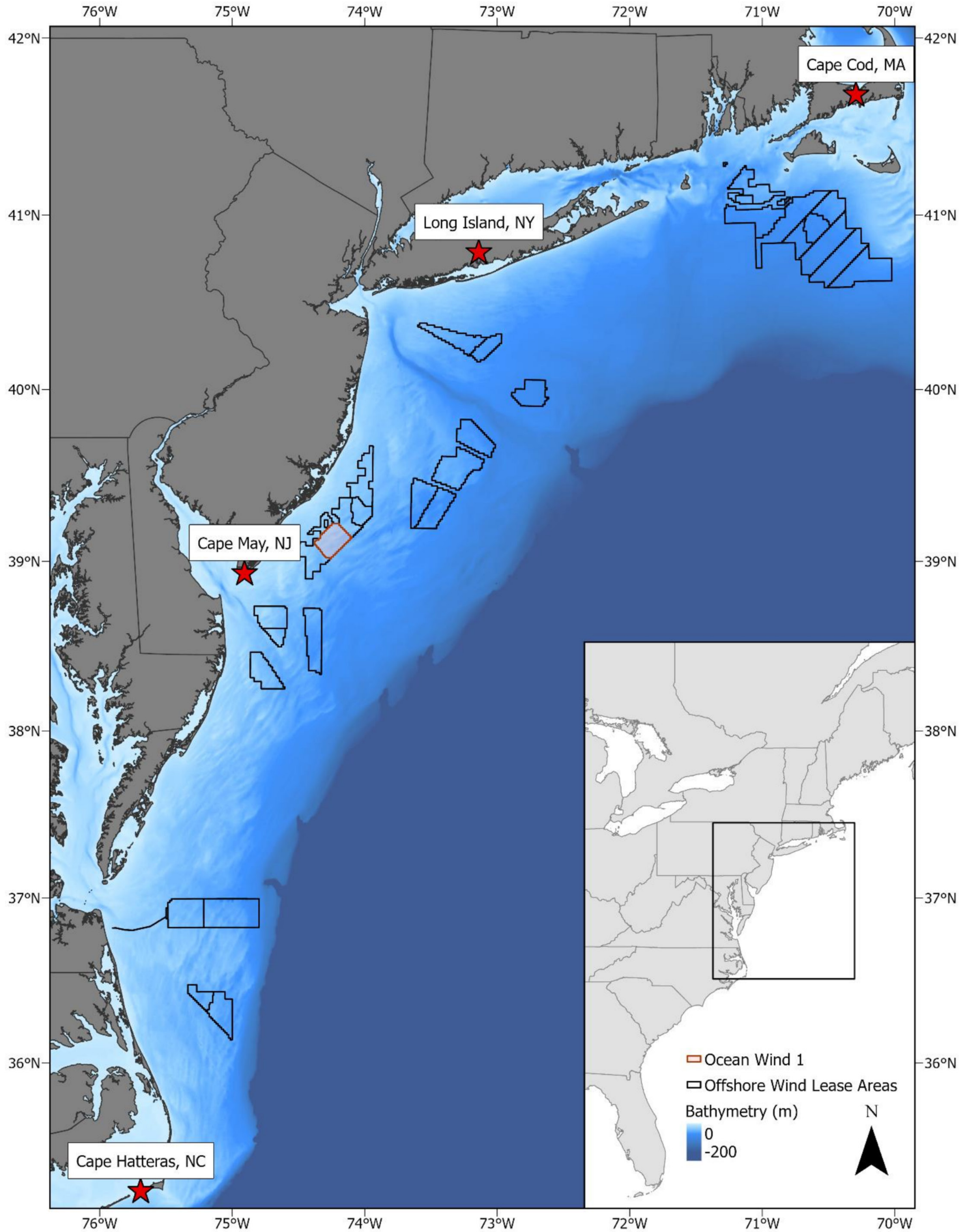

FIGURE 1 | Map of the Middle Atlantic Bight showing the location of wind farm leases and highlighting the Ocean Wind 01 lease. Inset shows the Bight's position along the US continental east coast.

changes to movement. These are not mutually exclusive. All have been proposed before (e.g., Ashley et al. 2018), but their effects and implications may differ in the MAB. The drivers acting on these ecological mechanisms include:

1. Wind turbine influences mixing of stratified water with consequences to primary and secondary production (Schultze et al. 2020; Golbazi et al. 2022).
2. Wind turbine placement changes fishing practices and catch and therefore fish communities (Szostek et al. 2025).
3. Wind turbines form artificial reefs and add intertidal habitat that could change predator–prey relationships, feeding habits, and fish community structure (Copping et al. 2021; Tharp et al. 2024).
4. The electromagnetic field of power cables might attract or hinder fish crossing and change migration or movement patterns (Gill and Desender 2020; Copping et al. 2021).
5. Turbine construction or operation noise could interfere with behavior including mate-seeking and predator avoidance (Copping et al. 2021).

Understanding these leads to testable hypotheses that compare measured change from that expected under oceanographic forcing alone. Hypotheses address measurable place-based "effects of development," such as change in fish assemblage or diet, with answers that can lead to action items such as compensation, stock assessment, or changes to a COP. These will typically differ from those erected to elucidate Impact Producing Factors, for example, exactly how reefing leads to competitive interactions between reef and sand-dwelling species, or what sound pressure level thresholds elicit a particular behavioral response by species. These are not place-based but are applicable to understanding and interpreting place-based effects of any development. Elucidation of development effects is addressed in the Study Design section. Impact Producing Factors are best addressed in experimental settings, including in laboratories, and are thus better suited for pursuit under research grant funds (e.g., pooled government-administered funds such as managed under ROSA or New Jersey's Board of Public Utilities), rather than the monitoring model of an FMP. That is not to say that collaboration should not also be extended to FMPs; in fact, FMPs would be well served by data sharing and regional, centrally funded OSW monitoring observatories (see Partnership for an Offshore Wind Energy Regional Observation Network, https://rwsc.org/boem-announces-poweron-program-partnership-with-rwsc/) and cooperation among independently funded lease-scale projects (see Atlantic Cooperative Telemetry Network further in this paper). These considerations guide the development of a statistical framework for FMP development.

2.1 | Statistical Framework

The FMP follows BOEM guidelines and begins before construction and continues during and after construction of a wind farm for a total of at least 6 years. However, it is important to note that being able to detect benthic and food web changes likely requires longer sampling periods (Degraer et al. 2020; Coolen et al. 2022), especially to be able to disentangle effects due to OSW development and other drivers of environmental change. Data collection in each site where a wind farm will be developed (i.e., impact sites) is matched by collection in a comparable site (Before After Control Impact [BACI]) where development is not occurring (i.e., control sites) or at increasing distance from the development site (Before-After Gradient [BAG]) design. These BACI and BAG designs anticipate that animal communities change for many reasons aside from windfarm development and allow changes due to turbines to be isolated (Methratta 2020, 2021). In particular, use of a BAG design acknowledges that the expansive spatial scale necessitated by BACI designs may miss important responses happening at shorter spatial scales and that "control" sites may not be very good controls (Methratta 2020, 2021), particularly when they might themselves be developed (become "impacted") as another lease during an FMP period.

Oceanographic features, especially circulatory drivers of temperature and oxygen, occur on the same spatial scale as impact or control sites and at the same temporal scale as sampling events. In the Mid-Atlantic Bight on the shelf, the known scales of oceanographic variability fluctuate in the along-shore and cross-shore directions for temperature, salinity, phytoplankton blooms, currents, and frontal boundaries. The spatial scales of coastal features and variability are approximately on the order of 20 km, often shorter in the cross-shore compared to the alongshore direction (Lentz et al. 2008; Wilkin et al. 2022; Beardsley and Boicourt 1981). These short scales of variability throughout the water column over the shelf are arguably more important than local benthic habitat structure (Manderson et al. 2009; Kohut et al. 2012) and thus challenge the interpretation of BACI/BAGs. Parallel to these challenges is a practical one; the ability to measure change is potentially compromised by the wind farm itself. Already, NOAA-NMFS has listed thirteen fisheries-independent surveys that will have to change from their historical random stratified sampling design due to a NOAA policy decision restricting survey vessel access and navigation through the lease areas (Hare et al. 2022). State and regional surveys could be similarly compromised, and loss of access by surveys can have important consequences to stock status indicators (Borsetti et al. 2023). Surveys for an FMP need to anticipate random sampling that considers the presence of turbines and power cables after construction. Finally, the extent of planned OSW development in the region, if accompanied by FMPs that use capture-based sampling methods at each lease area, increases the potential for cumulative detrimental impact on protected species (e.g., Atlantic sturgeon and sea turtles, Cheloniidae and Dermochelyidae, North Atlantic right whales, *Eubalaena glacialis*) by the surveys themselves. Thus, the statistical framework always considers oceanographic effects in partitioning the variance of a response. Broadly considered, these variance partitioning models include generalized linear/additive methods (GLMs/GAMs) and decision trees such as random forest or boosted regression (Dietterich 2000). Since these models can accommodate variables and factors (i.e., categorical and ranked data) and their interactions, they will include and measure the explained variance (in GLMs and GAMs) or importance (in decision trees) of categories before/after and control/impact or gradient distance relative to oceanographic features.

We designed and began studies for FMPs of the Ocean Wind 01 (OW1) windfarms and control sites in 2022 and 2023 as well as

TABLE 1 | Survey-specific modalities.

Survey	Sample timing	Instrument/bait	Duration
Bottom Trawl	Seasonally (4×/year)	None	Tow specifications followed NEAMAP protocols: 20-min tow at ~3 knots
Surfclam	Annually (1×/year)	None	Tow specifications: 5 min ~ 2.5–3.0 knots
Structured Habitat	Seasonally (4×/year)	BRUVs/~1.5 kg chopped Atlantic menhaden	60-min soak
		Chevron trap/~6.0 kg whole Atlantic menhaden (*Brevoortia tyrannus*)	90-min soak
		Rod-and-reel: frozen Atlantic surfclam (*Spisula solidissima*)	3 × 8 min-drift transects
Pelagic Fish	BRUVs: Seasonally (4×/year)	BRUVs/~1.5 kg chopped Atlantic menhaden	BRUVs: 60-min soak Glider: 3- to 4-week missions
	Active Acoustic Gliders: Fall	None	Towed: ~25–30 km tracks for 8–10 h missions
	Towed camera:	TrollPro camera housing is lure	Towed continuously between sample sites, vessel coordinates interpolated to image timestamps
eDNA	Concurrent with trawl survey	Bottle/none	Two or more 1-L water samples 20 m from surface
Glider	Concurrent with trawl survey (fall for Orsted, quarterly for ASOW)	Slocum G2 and G3/None	?
Acoustic Telemetry	Continuous All glider deployments Deployed from vessel on eDNA/Trawl stations	Innovasea VR2-W receivers or later and compatible transmitters/none Innovasea Rx-Live Innovasea VR-100-300	Moored continuous, downloaded quarterly Mission duration During station occupation

Atlantic Shores Project 1 and 2 in 2024. Although both companies ultimately postponed the pursuit of their projects, a number of lessons were learned prior to and during the plan development and initial sampling. The efforts were composed of multiple coordinated and complementary surveys including a bottom trawl survey, environmental DNA (eDNA) survey, structured habitat survey, Atlantic Surfclam (*Spisula solidissima*) dredge survey, pelagic fish survey, acoustic telemetry monitoring, and oceanographic data collection (Table 1, Figure 2). Treatment of specific response data types is described in their respective sampling methods sections. All of these efforts began prior to construction in order to accommodate BACI factors or gradients in their analysis (Methratta 2020, 2021). The methods also serve each other in that response variables from one survey may be used as explanatory variables or leverage interpretation in another (e.g., acoustic telemetry detection of migration timing may help interpret local change in abundance in seasonal surveys). Finally, oceanographic sampling must and does occur on a scale that captures regional features in order to interpret and frame phenomena such as migration phenology that could appear erroneously as OSW development effect. That scale of sampling by default captures variation across other OSW leases, including those predevelopment or in development. If data are freely shared, as they are for the projects we demonstrate here, then unification advances towards default.

2.2 | Study Site

In this paper, we detail Ørsted's OW1 study site for examples of specific site-based challenges to FMP development. The 68,450-acre lease is located 24 km offshore from Atlantic City, a coastal urban resort and hub for both commercial and recreational fishing. This lease is positioned on the inner third of the continental shelf offshore of New Jersey, USA, near an estuarine inlet (Absecon Inlet) (HDR 2022; Figures 1 and 3). Water depth ranges from 18 to 36 m with a mode of 25 m, with a slope approaching 1°. The seabed consists of unconsolidated sediments.

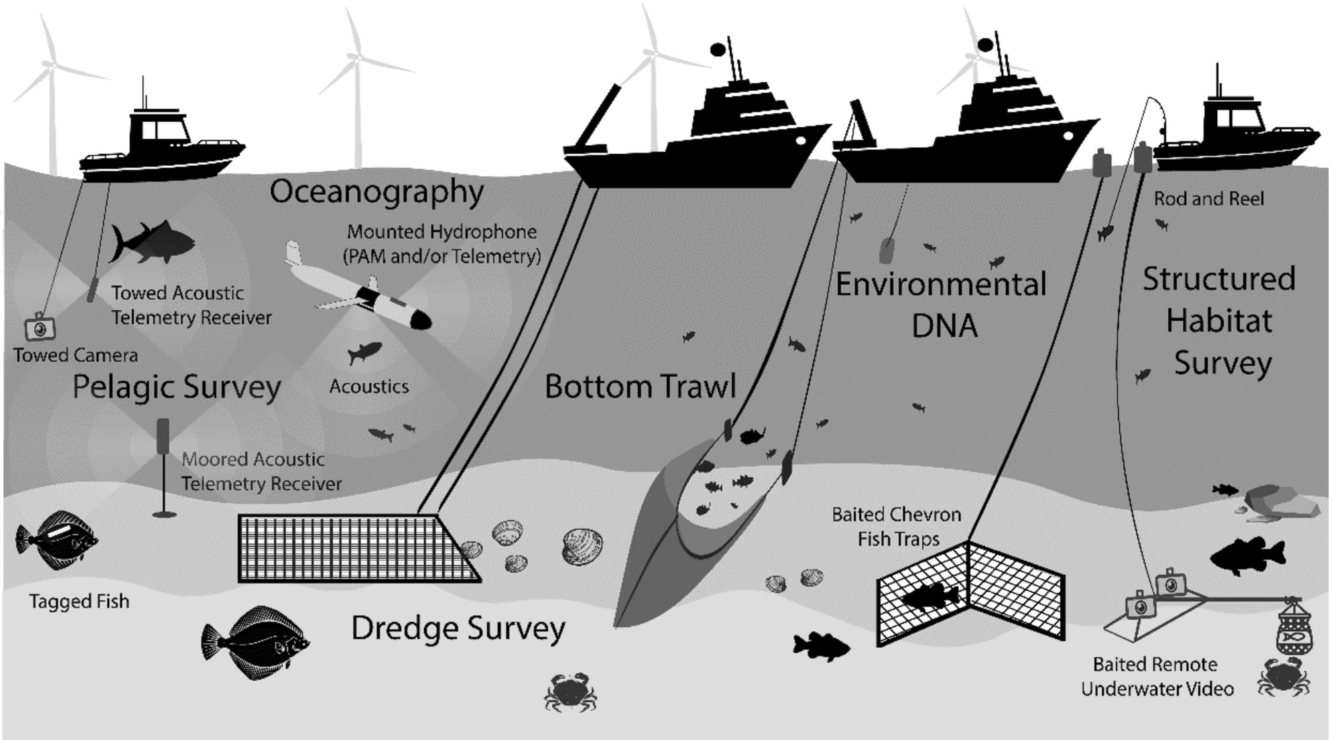

FIGURE 2 | Survey tools include extractive and nonextractive methods for pelagic, epi-benthic, and benthic fisheries resources in soft and hard bottom habitats in addition to those for monitoring the physical environment. Remote sensors (not displayed) also play an important role.

Sand ridges (swales) are present but less so than in areas adjacent to the lease. The development plan included three substations and up to 98 turbines in a roughly rectangular grid with 0.8–1 nautical mile (1.48–1.85 km) spacing. Turbines would be supported on monopiles driven into the ground and protected by rock scour revetments. Inter-array and export cables would be buried at a target depth of 1.2–1.8 m below sediment.

The choice of control sites was challenged by the presence of adjacent leases. The timetables for the development of those sites were unknown and not under the control of the Ocean Wind 1 project. Furthermore, controls for different survey modalities required varying considerations, such as the presence of reef structure or a history of fishing exploitation. Therefore, bathymetry, fishing effort, the location of adjacent lease sites, patterns of fishing effort, and other factors were considered to identify representative control sites for each survey. For example, a raster file of bathymetry was iteratively sampled to converge on an "L"-shaped control site for trawling that was similar in depth and rugosity profile to the impact site (Figure 3).

2.3 | Oceanography at the Forefront

The OW1 study site is situated on the inner continental shelf of the central MAB. The physical oceanography of this region is influenced by local topography, freshwater input from the Hudson River and Long Island Sound, large-scale atmospheric patterns over the North Atlantic, and tropical or winter coastal storm events. Therefore, ocean characteristics within the study site undergo remarkable variability across time scales from days and weeks to seasons, years, and decades. Seasonally, this area experiences one of the largest transitions in stratification with cold, well-mixed conditions in the winter months and strongly stratified conditions during the summer (Houghton et al. 1982). In late spring and early summer, a strong thermocline develops at about 20 m depth across the entire shelf, isolating a continuous mid-shelf "Cold Pool" of water that extends from Nantucket to Cape Hatteras (Houghton et al. 1982). Local river discharge can augment this thermal stratification across most of the shelf (Chant et al. 2008; Lentz 2017) and provides pulses of nutrients and other material to the MAB shelf. These riverine inputs are only a fraction of the supply from upstream sources delivered by a mean southwestward flow along the shelf (Fennel et al. 2006). In addition, upwelling along the coast occurs annually each summer, driven by southwest winds associated with the Bermuda High (Glenn and Schofield 2003; Glenn et al. 2004). Local upwelling can deliver Cold Pool water all the way inshore and to the surface near the coast (Glenn et al. 2004). This upwelled water can drive the development of very large phytoplankton blooms that are advected offshore (Sha et al. 2015).

This intense ocean variability drives a highly dynamic ecosystem from the primary producers (Malone et al. 1988) to the highly migratory fishes and mammals throughout the study site. The tight coupling between the ocean conditions and the habitat preference of the commercially and recreationally targeted species leads to strong seasonal variation in species composition and distribution that is overlaid on annual variation such as migration. Given this connection between the physical oceanography and the fisheries throughout the study site, ocean measures, particularly those characterizing the progression of seasonal stratification, need to be associated with each of the survey components described below.

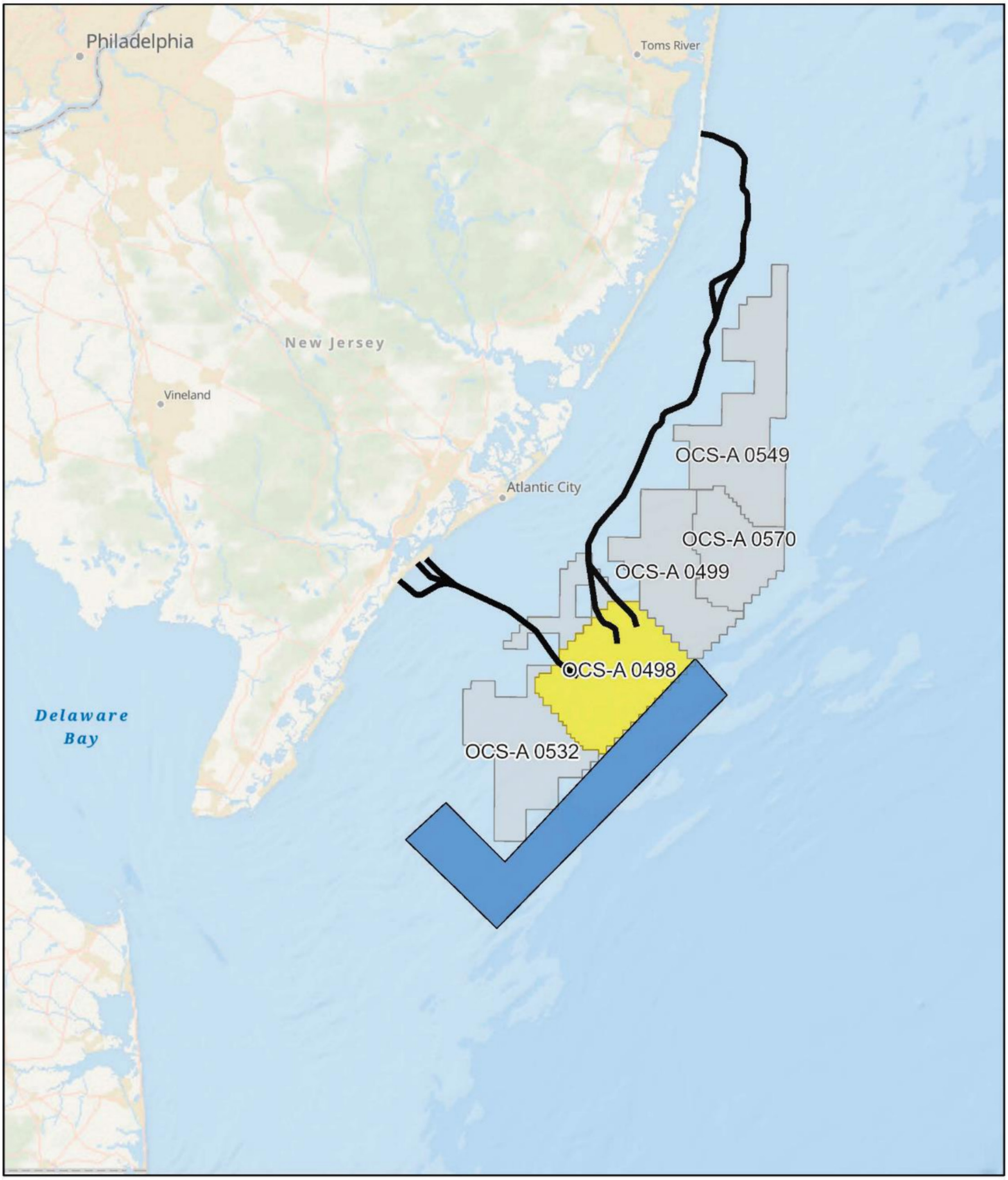

FIGURE 3 | Lease area and project boundaries of Ocean Wind 01 (yellow area) located off New Jersey, USA. Boundaries of the control site for the bottom trawl survey (in blue) were selected based on distribution of bathymetric profile constrained by adjacent leases. Surrounding OSW lease areas are represented in orange (Ørsted Ocean Wind 2) and grey (Atlantic Shores Offshore Wind LLC). Export cable routes are black.

The impact of OSW development in the MAB may differ from that caused by European installations because of stratification, strong seasonal influences, and the depth at which some of these windfarms are being built (Miles et al. 2021). The MAB experiences among the highest annual temperature ranges (~30°C) and seasonal stratification of any marine province (Biscaye et al. 1994; Mountain and Taylor 1998). This pattern is under the influence of a mid-latitude insolation curve and the contribution of cold southerly and relatively fresh flows from the Gulf of Maine and warm salty input from the south (Gulf Stream and its related intrusion features). Freshwater enters from estuaries of local watersheds (Hudson, Delaware, Chesapeake). The combination of seasonal estuarine plumes, vernal heating, and cold subsurface intrusions leads to the marked stratification of the shelf water that reaches a summer maximum with the isolation of the Cold Pool and eventual mixing with the onset of autumnal storms, such as hurricanes and nor'easters (Churchill and Cornillon 1991a; Churchill and Cornillon 1991b; Lentz 2003; Chen et al. 2018).

As a result of this thermal range, many of the species that utilize the MAB shelf waters migrate seasonally (Colvocoresses and Musick 1984). Therefore, seasonal timing is an important constraining factor in monitoring fisheries resource response. Species assemblages and distributions are projected to change even in the absence of any OSW development as a result of climate change (Kleisner et al. 2017; Tanaka et al. 2020). Anticipated changes are already reflected in the alteration of target species by commercial fishers, including increased abundance of southern affiliated coastal sharks, dolphinfish (*Coryphaena hippurus*), and cobia (*Rachycentron canadum*); continued increase in summer flounder (*Paralichthys dentatus*); and decreases in the north or cool-affiliated species such as goosefish (*Lophius americanus*), winter flounder (*Pseudopleuronectes americanus*), lobster (*Homarus americanus*), and Atlantic surfclam (Hofmann et al. 2018). However, a retreat in cool-affiliated species may also occur as an offshore shift in the population center, resulting in a relative increase within OSW lease areas for nearshore species such as surfclam (Narváez et al. 2015), one of the most economically productive in the MAB (Munroe et al. 2022; Scheld et al. 2022).

2.4 | Designing a Fisheries Monitoring Plan for MAB OSW Development

Given the tight coupling between the highly variable oceanography and fisheries across our study site, our approach classifies fisheries metrics tracked through our survey to specific ocean conditions related to the seasonal evolution of stratification. To resolve the scales relevant to our fisheries metrics, we deployed an autonomous underwater vehicle (AUV) concurrent with the seasonal fisheries surveys. Our Slocum glider provided surface to bottom profiles of ocean temperature, ocean salinity, ocean density, dissolved oxygen, depth-averaged ocean currents, and the observed distribution of primary producers. In addition to these core physical and biological oceanographic metrics, our glider was equipped with an active acoustic sensor providing simultaneous estimates of fish distribution relative to the evolving oceanography. Additionally, we conducted concurrent oceanographic sampling from our survey vessels to complement the broader scale survey of the glider. The combined data collection from our glider and the survey vessels was timed to cover the seasonal fisheries survey activities within and surrounding the study site. Together, they are designed to characterize the changing environmental conditions at key times in the seasonal progression of stratification coincident with our fisheries metrics. Given the overlap between our study site, these oceanographic surveys leverage the significant regional ocean observing infrastructure in a way that ensures our data collection and analysis are done within known regional environmental conditions, maximizing the opportunity to isolate potential fishery impacts from OSW development at our study site from the significant short and long-scale variability in this region (Figure 4). This integration is facilitated through the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) and the Rutgers Center for Ocean Observing Leadership (RUCOOL). MARACOOS has provided physical ocean observations and predictions of the coastal ocean overlapping with the Ocean Wind Study site for more than a decade. RUCOOL has been a central player in the implementation and application of these data to various activities in the region, including beach water quality (partnering with the New Jersey Department of Environmental Protection and local municipalities, among others), coastal storms (partnering with NOAA, among others), fisheries (partnering with commercial fishers, NOAA, among others), and OSW (partnering with New Jersey Board of Public Utilities, Ørsted, among others). We leverage all these partnerships to deliver fundamental physical and biological ocean measures to the survey analytics. This allows us to quantify the connection between our target species and the ocean characteristics that will be critical to accurately assess changes through the preconstruction, construction, and postconstruction phases of the OW1 project.

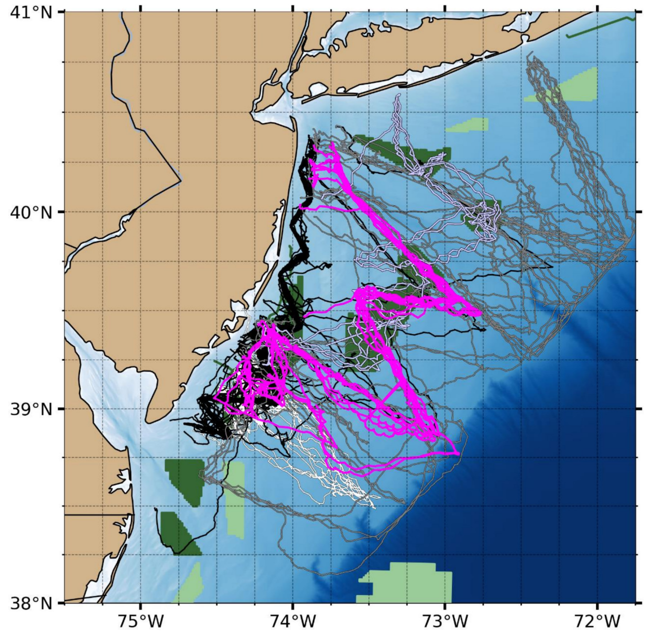

FIGURE 4 | Glider missions specific to measuring windfarm effects on oceanography and fisheries resources of the Ørsted Ocean Wind 1 development (ECO-PAM, white track) are superimposed on regional observatory missions that cover the broader study area, including those commissioned by the New Jersey Department of Environmental Protection (black tracks, 2014–present), Research and Monitoring Initiative (magenta tracks, 2023-present), the New York State Energy Research and Development Authority (light pink tracks, 2023–2025), and other various projects supported by National Science Foundation, National Oceanic and Atmospheric Administration, or New York State Department of Environmental Conservation (grey tracks, 2018-present). OSW lease and planning areas are shaded light and dark green.

2.5 | Integrated Collaborative Team

A diversity of collaborators was included in the design and execution of our FMP to improve the ecological relevance of surveys and the utility of results. Assembling a multi-institutional research team with expertise in a range of disciplines (e.g., physical and biological oceanography, fisheries biology, survey design, and stakeholder engagement) aided in the development and execution of an integrated FMP that incorporated multiple complementary surveying approaches. Inclusion of scientists representing an OSW developer helped to address local issues related to the windfarm site, including consideration of regional and global issues related to OSW development and lessons learned from monitoring other windfarms. Having surveys led by university-based researchers is expected to have aided in transparency and perceptions of objectivity among stakeholders (Johnson and van Densen 2007).

Fishing industry members bring valuable fishery, ecological, economic, social, and institutional knowledge into research collaborations (Stephenson et al. 2016). For our FMP, fishing industry involvement aided in the development and execution of effective surveys by incorporating their local ecological knowledge (e.g., species' phenology and assemblages) and expertise associated with survey gear rigging and deployments. Several of the surveys within our FMP have included collaboration with commercial fishing industry members, including (a) bottom trawl survey, (b) structured habitat survey, (c) surfclam dredge survey, and (d) acoustic telemetry measures. Conducting several surveys aboard commercial fishing vessels also likely aided in improving the relatability and transparency of results among other fishing industry stakeholders (Runnebaum et al. 2019) who have often been critical of OSW development in the northeast US region (Ten Brink and Dalton 2018; Ryan et al. 2019). This industry collaboration and other stakeholder engagement efforts related to our FMP (e.g., presenting at scientific conferences; presentations to local fishing industry groups) have aided in mitigating conflict among the fishing industry and OSW development (Haggett et al. 2020).

Conducting these surveys in collaboration with commercial fishing industry members presented additional challenges for OSW monitoring beyond those typical of cooperative research in our region (e.g., building partnerships and trust, disruptions to fishing schedules). For example, our fishing industry collaborators showed some initial hesitation about participating given concerns that their industry peers might view them as being supportive of OSW development, fomenting resentment in the industry. These concerns were ameliorated following discussion of the need for these surveys to investigate the potential impacts of OSW development on fisheries resources and the need to have experts from the fishing industry involved to effectively execute these surveys. Additionally, with this FMP being funded by a developer, there were stringent health, safety, and environment (HSE) requirements to ensure the safe and responsible operation of all vessels and survey activities. Trainings include marine survival training (STCW, AMSEA or similar), could include licensing requirements or RADAR training for captains and mates, marine mammal identification, resuscitation for protected species, and stringent documentation, reporting, and the use of "toolbox talk" safety and best practices briefings. Sometimes these requirements can change based on the construction phase, such as with daily deconfliction meetings with the developer when sampling is co-occurring during the construction phase, leading to a large time commitment. The extent of these HSE requirements had not been previously experienced by our fishing industry collaborators—or by many researchers involved. Associated tasks, some extending multiple years, challenged industry commitment due to frustrations associated with the necessary time commitments and related conflicts with lucrative fishing opportunities. Our close collaboration with fishing industry partners to meet these challenges in ways proposed by the fishing community serves as a useful model for developing and executing monitoring programs for OSW development in other regions of the US and around the world.

2.6 | Anticipatory Impact Study Design

BACI and BAG survey designs are effective approaches for evaluating the impacts of natural and human-induced disturbances (Christie et al. 2020; Methratta 2020). Therefore, both are recommended to measure how the construction and operation of windfarms affect natural resources (ROSA 2021). However, the placement of wind turbines and export cables within the lease area is anticipated to lead to sampling constraints once construction begins. For instance, expanded scour or scour protection (Whitehouse et al. 2011; Guan et al. 2022) near turbines or over cabling routes might make it difficult or impossible to tow standard bottom sampling or fishing gears in some places. Failure to account for these constraints when planning a survey could lead to changes in methods at one or more stages of the BACI or BAG design. For instance, some areas sampled during the "before" stage may no longer be accessible during the "after" stage, or it may be necessary to change the type of sampling gear used to allow for safer sampling or navigation. Such changes would violate key assumptions of BACI and BAG designs by not permitting standardization of sampling methods or randomized selection of sites within control and impact sites (Methratta et al. 2020). As a solution to this problem, we designed sampling to occur at the "before" stage as if the windfarm infrastructure was already in place. To allow for this, we requested information on the orientation, spacing, and geometry of the planned windfarm infrastructure and used this to develop a virtual representation of the layout. This "virtual windfarm" was then used to create strata that will remain safe to sample throughout the project life. Additionally, given the size of these strata, we considered how safely different sized vessels and gears can be deployed and retrieved once the windfarm is constructed. For example, a bottom trawl may be the most appropriate and efficient gear for evaluating impacts to benthic and epibenthic fisheries resources and work well during the "before" stage, but given turbine spacing at some windfarms, may not deploy and retrieve safely once the windfarm is constructed. We found it to be important to scale the size of the gear and vessel accordingly, shorten the tow duration, and it may be necessary in some cases to use a different gear altogether that can sample consistently across all three stages of the BACI/BAG design.

For our FMP, we collaborated with the developer to create a virtual map of the wind farm infrastructure at OW1 (Figure 5). The developer provided shapefiles for each planned turbine, the

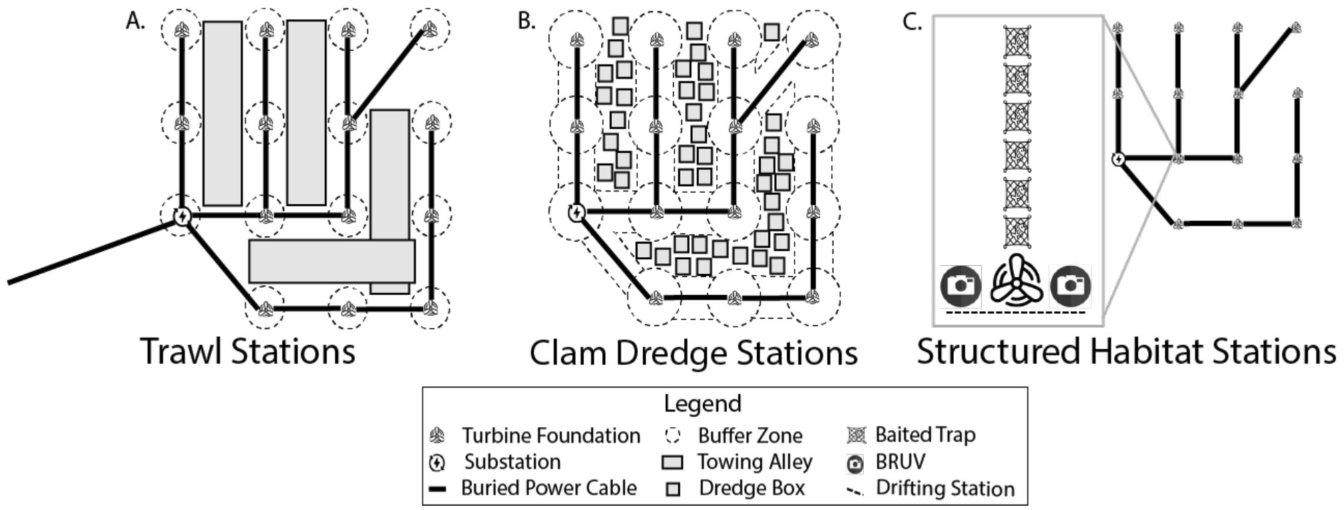

FIGURE 5 | The panels show a simplified version of a sample plan through a planned wind farm area. Panel A shows the trawl stations through the OSW area with a buffer around the proposed turbine foundations. Panel B shows the clam dredge stations with a buffer around the proposed turbine foundations and cable routes. Panel C shows the structured habitat stations with BRUV stations on both sides of the proposed turbines, six baited Chevron traps in a line with a gradual increase in distance from the proposed turbine foundation, and a drifting station near the proposed turbine foundation for rod-and-reel sampling. In all cases, the icon marking the turbine location slightly overapproximates the proposed extent of scour protection around each turbine.

cabling routes between turbines, and the location of each offshore substation. These shapefiles were uploaded to the plotter of the vessels used in each survey that may be affected by the wind farm infrastructure. Below, we provide examples from three surveys that used the shapefiles of the wind farm infrastructure to design a survey that would remain standardized during each construction stage.

For the trawl survey, we consulted with our industry collaborator to establish a virtual 0.25 nautical mile (nm) buffer around each turbine. This buffer was meant to ensure the survey vessel would remain a safe distance away from any planned turbines. Towable alleys/boxes, 2 nm long and 0.5 nm wide, were then randomly placed and oriented within the wind farm so that no strata overlapped with a part of the virtual infrastructure or any virtual turbine buffer. Completely filling the grid of possible alleys (beyond the number of planned tows) and choosing randomly from that grid prior to a survey buffers for adaptive changes to the survey, including minor changes in the as-built location of turbines. The 2-nm strata length was chosen because it was approximately twice the standard average tow distance from the Northeast Area Monitoring and Assessment Program (NEAMAP) survey (Bonzek et al. 2007), which is a regional bottom trawl survey that is being modeled for OSW FMPs to facilitate regional coordination of survey methodology. Doubling the towable alley length provides flexibility for the specific locations of 1 nm safe and effective tows, allowing the captains to adjust for nearby vessels, variable weather, or potential gear hangs on the bottom, while still maintaining a sufficient number of viable alleys within the lease area. This distance also ensures safe deployment and retrieval of the trawl net before any interaction would occur with wind farm infrastructure. The same size and number of strata were then randomly placed and oriented within a nearby control area of similar size, depth, and physical habitat characteristics. The same vessel used for the Mid-Atlantic NEAMAP survey (*FV Darana R*) was used in our FMP trawl surveys, as well as the same crew, net, doors, configuration, speed and duration. Only tow direction differed in that it had to conform to the phantom alleys.

The surfclam survey component of our FMP followed standardized methods that will allow integration with regional surveys (Munroe et al. 2023) and used a similar approach to overcome challenges of sampling after OSW construction. The exceptions in the case of the surfclam survey design were that the offset buffer around each turbine was set to 0.35 nm to allow buffer around scour or scour protection around the base, a 0.2 nautical mile (370 m) buffer around buried cables, and the sample box size was 0.3 nm (557 m) per side, which allowed sufficient area to make short standardized tows within the bounds of the box in any direction (Figure 5). In addition, a stratified approach was used to delineate survey areas that differed in terms of surfclam habitat. The OSW survey area was divided into two equal strata, with one stratum shallower in depth and having relatively less recent commercial fishing effort. Nearby control sites were identified that matched each stratum in area, water depth, fishing effort, and bottom sediment type. Finally, in an effort to minimize safety and maneuverability challenges for the survey once the OSW project is fully built out, the survey platform selected for the surfclam survey was a vessel that is 30 m (99 ft) long, which is among the smaller vessels in the commercial surfclam fleet and used a fully calibrated hydraulic dredge (Munroe et al. 2025) to collect samples.

Our Structured Habitat Survey was also designed with anticipation of disruptions after construction. For example, the spacing of trap deployments during all survey phases was accounted for taken into account the presence of the turbines even before they would have been constructed, whereas the first trap was deployed 60 m from the sites of planned turbine construction and then the subsequent traps were deployed with 150 m spacing (Figure 5c). This spacing permitted sampling near the turbine and also a distance that is approximately halfway to the next planned turbine in the windfarm. Similarly, the benthic and pelagic baited remote underwater videos (BRUVs) were deployed 60 m from each selected location, including the planned turbine locations, the "phantom turbine" locations used as sand controls, and shipwrecks on a nearby artificial reef, which were designed to all be held constant before, during, and after construction. The distance of the closest sample was based on plans in the COPs and risk tolerances expressed by a collaborating captain and buffers for the uncertainty in the final built position of the turbine. It targets the edge of the proposed scour revetment but is not in it. Scour may change the bottom beyond planned scour protection (Whitehouse et al. 2011; Guan et al. 2022). Reef fishes such as black sea bass (*Centropristis striata*) shelter on the reef but may forage in sand habitat and make excursions between adjacent habitats (Jensen et al. 2021), with the probability of occurrence from purely random movement thus decaying inversely to the increase in the area of a circle. This initial placement may miss sharply increased concentrations of fish due to structural attraction at a very small (1–5 m) scale, which can be addressed by the multimodal approach of acoustic telemetry, video, and hook and line fishing (see below). The sampling conducted with rod-and-reel also anticipates turbines and their safe approach from drifting vessels versus anchored vessels. Timed fishing drifts standardize the drifts before, during, and after construction at all survey stations.

2.7 | Meso-Predator Trophodynamics

Shift in feeding habits of fish can be expected as a result of reefing and other changes to benthic structure through the introduction of large numbers of suspension feeders and reef-oriented fishes to an area formerly dominated by sand-oriented species (Hutchison et al. 2020; Grothues et al. 2021; Tharp et al. 2024; De Borger et al. 2025). Analysis of change in the diet of two signature species, a sand-obligate flatfish, summer flounder (*P. dentatus*), and a reef-facultative black sea bass fits into the same statistical framework as the previously described survey modalities, with gut content summarized into independent univariate "sample scores" reduced from ordinations such as principal components analysis, gut fullness, or index of relative importance. Methods follow those used by the NEAMAP survey, targeting up to three fish/size class/species/tow of three size classes (Chesapeake Bay Multispecies Monitoring and Assessment Program 2011). In addition, the amount of change in classified samples of the Control and Impact sites from After is tested for change against the Before group using Hamming's Loss, which calculates an error rate as the percent of items in an a priori class that are flipped into another class after a change. Sampling for this goal is integral with the trawl survey as the source for guts (but not hook and line, which may be biased to hungry or bait-focused individuals) and is thus anticipatory in the same way as trawling.

2.8 | Nonextractive Techniques

Nonextractive sampling methods (e.g., environmental DNA [eDNA], BRUVs and towed cameras, AUVs, acoustic telemetry) are warranted to mitigate further impacts to protected species and other fisheries resources and to mitigate for loss of extractive survey access (e.g., Hare et al. 2022). In addition, academic and federal research programs have struggled to maintain vessel-based observation efforts due to ship time becoming increasingly costly (Reiss et al. 2021). Finally, extractive survey methods often have unavoidable negative impacts on habitat and organisms. This is especially a concern for Atlantic sturgeon. This federally listed endangered species uses both habitat close to shore at cabling sites (Ingram et al. 2019; Rothermel et al. 2020; Shipley et al. 2024) and habitats on the continental shelf associated with estuarine plumes and benthic features. Given the concern over their stock status (NOAA 2012), bycatch issues in some commercial fisheries (Stein et al. 2004), and a life history dependency on electrosensitivity (Zhang et al. 2012), Atlantic sturgeon deserve continued study in the area. Furthermore, leveraging recent advances in eDNA reduces the need for large sampling gear and enables access with much smaller and lightly crewed vessels along with integrating autonomous observation platforms. Concerns of vessel and crew size additionally counteract event-based disruptions such as the recent COVID pandemic or major storms, as a central component of our study design.

Beyond abatement of risk to harm of the environment being monitored, these nonextractive methods may provide novel and insightful data that trawls and traps cannot. However, because these methods are not yet as established compared to extractive sampling methods, including bottom trawls and traps, in terms of understanding sampling bias and interpreting results, there is some hesitancy in funding biomonitoring projects that heavily rely on nonextractive methods, which has slowed their development. Therefore, comprehensive inclusion of a wide range of established techniques alongside nonextractive techniques, such as eDNA, BRUVs, and towed cameras for pelagic fish distribution in lieu of gillnets, will enable continued access, limit cost, and minimize impact on ecosystems being surveyed. It will also advance our understanding of how these methods compare to each other, which will help a transition to less intrusive ocean observation.

2.8.1 | eDNA

eDNA was the first type of biological sampling to begin in our FMP as there was no need to wait for permitting. A distinct shift from developing and optimizing eDNA tools to integrating it as a standard approach in biomonitoring programs has already been observed in freshwater systems (Schenekar 2022). Research into how to most effectively integrate eDNA into marine fish community assessments has accelerated in recent years (Hinz et al. 2022). The growing excitement for the same to occur in marine systems is built around the potential impact this tool can have, especially in terms of spatial resolution, access to habitats that currently cannot be safely sampled with traditional methods, limiting habitat impacts, and minimizing mortality associated with sampling. Recently, the US White House issued a National Aquatic Environmental DNA Strategy (White House 2024) that specifically calls out monitoring of OSW as a suitable use case scenario for eDNA technologies. Recent studies coupling capture surveys with eDNA sampling have effectively demonstrated that metabarcoding data sets can be used for more than detecting species presence. Both the number of observed species and relative abundance are comparable among data sets (Thomsen et al. 2016; Stoeckle et al. 2020; Stoeckle et al. 2021; Stoeckle, Adolf, et al. 2022), thus allowing for an effective characterization of changes in community structure over time using eDNA.

Establishment of evidence-based best practices for use of eDNA in biomonitoring (Andres et al. 2022; Hinz et al. 2022; Beng and Corlett 2020; Kelly et al. 2019) is a critical factor supporting its use in fisheries monitoring plans for OSW development. The "gear bias" and best sampling practices of eDNA surveys, as is true for traditional surveys, need to be acknowledged and inform study design and interpretation of the data. For example, analysis of capture surveys must account for well-studied gear bias associated with nets and traps (Andres et al. 2022), while acoustic telemetry detection is highly dependent on the number of acoustic tagged fish in a region, tag power, and array configuration (Brownscombe et al. 2019; Kessel et al. 2013). In both cases, the method itself creates bias in the results that can be accounted for using study design and standardized laboratory practices.

Gear bias in eDNA surveys using metabarcoding can arise due to (1) the characteristics of eDNA distribution and persistence in the environment and (2) technical artifacts during processing in the lab and the bioinformatics process. First, unlike trawl surveys which only capture individuals in the area towed, experiments suggest that in marine environments eDNA is detectable for ~48 h (Collins et al. 2018) and detections of eDNA may be observed from 1 to 10s of kilometers away from the source, depending on prevailing currents (Andruszkiewicz et al. 2019; Shea et al. 2022). As a result, detections represent the recent presence of a given fish species over a certain spatial and temporal scale. Similarly, the spatiotemporal resolution of traditional capture surveys is generally limited by the cost of ship time. By contrast, eDNA surveys can be designed at a finer spatiotemporal scale. In combination, the higher spatiotemporal resolution of eDNA surveys along with the ability to detect individuals within a certain area of sampling can additionally help smooth out the assumed patchiness of species' distribution due to the design of capture surveys. It is important to acknowledge that species may be more likely to be overrepresented or misidentified because of primer bias and amplification-efficiency distribution across taxa being targeted (Kelly et al. 2019), although protocols to account for this are being tested (Stoeckle, Ausubel, and Coogan 2022). Finally, the quality of the reference libraries used in metabarcoding approaches will affect the taxonomic resolution and completeness achieved (Beng and Corlett 2020; Stoeckle et al. 2020).

A key advantage deriving from this characteristic of eDNA analyses of fish communities is the ability to detect the presence of rare species that have lower probabilities of being captured in nets, as evidenced by the detection of the Gulf Kingfish and Brazilian Cownose Ray, two unexpected species, in an eDNA metabarcoding survey of NY Harbor (Stoeckle et al. 2020). As a result, community assessments using eDNA compared to trawls will give a snapshot of the community that is integrated over broader space and time compared to a trawl, with the benefit of eDNA having more species being detected, including rare and elusive species and species with more patchy distributions. Overall, the advantages of eDNA in the context of fisheries monitoring plans include (1) relatively low cost and high throughput compared to traditional capture methods; (2) nonextractive and nonlethality in censusing marine fish populations, which allows for monitoring of species listed under the US Endangered Species Act (ESA) without the need for additional federal permits; (3) simple sampling methods that require smaller and less expensive vessels and access to habitats that cannot be trawled; and (4) the dispersed nature of eDNA compared to the patchy distribution of fishes leading to more detections of rare species (e.g., ESA listed Atlantic Sturgeon) despite less sampling effort. As a result, eDNA surveys are poised to play a central role in monitoring the effects of OSW turbines on fish assemblages, especially during construction and once turbines are operational and trawling access to sites may become increasingly limited. In the context of using eDNA metabarcoding in a BAG/BACI experimental design, "fish community composition" determined through multivariate (Liu et al. 2019) or machine–learning classifier approaches (Yu et al. 2025) would be an appropriate response variable (rather than absolute abundance that might be used in capture surveys). For qPCR, absolute gene abundance, which has been shown to correlate with absolute fish abundance (Shelton et al. 2022), may be used for single species of interest. Additionally, the lower cost, simpler, and less time-consuming sampling protocols combined with faster processing will enable sampling at higher resolution than is typical of trawl surveys. Higher resolution sampling is especially important for understanding temporal and spatial variability and being able to evaluate impacts of OSW against a background of other influences on fish community composition including natural spatiotemporal variability and climate change.

2.8.2 | BRUVS and Towed Cameras

Multiple valuable guides inform BRUV application for surveying fishes in the Study Area and control sites (e.g., Birt et al. 2021; Harvey et al. 2021). BRUVs are an important part of structured habitat surveys even absent the concern regarding extraction, because they are appropriate to habitats that cannot be trawled and are less biased than hook and line or traps to certain species. BRUVs can monitor a suite of commercially and recreationally important species from video systems deployed on the seafloor, such as black sea bass, scup (*Stenotomus chrysops*), grey triggerfish (*Balistes capriscus*), tautog (*Tautoga onitis*), and spiny dogfish (*Squalus acanthias*). Concurrent deployment of a pelagic BRUV system is useful for monitoring pelagic species that are important to commercial and/or recreational fisheries and expected to seasonally occupy the Study Area and control sites, such as cobia (*R. canadum*), bluefish (*Pomatomus saltatrix*), dolphinfish (*C. hippurus*), Spanish and king mackerel (*Scombroides* spp.), little tunny (*Euthynnus alletteratus*), and sharks. However, BRUVs disproportionately attract scavenger and predatory species, potentially overrepresenting these groups while underrepresenting species less attracted to bait (Cappo et al. 2004). Towed or autonomous vehicles acting as BRUVs have a limited attraction range; a fish must be within a sensing/reaction distance of them. Therefore, surveys crossing and extending beyond impact areas can find the decorrelation scale between video sightings of individuals and constructed, benthic, or hydrographic features. Numerous simple hobby cameras can be crowd-sourced to sport fishers with instructions for synchronizing camera clocks with GPS records, both of which are returned and processed to create probability distributions from the cumulative transects (see Grothues et al. 2017 for an example from AUV mounted cameras) and fitted to lease, topographic, or hydrographic layers.

2.8.3 | AUV/Gliders

There is a need to test the potential for autonomous underwater platforms, such as gliders, to augment or replace current vessel-based efforts, specifically for fishery-independent surveys conducted through NOAA National Marine Fisheries Service Northeast Fisheries Science Center (NMFS NEFSC) Ecosystem Monitoring and Ecosystems Surveys groups. While significant progress has been made in using autonomous vehicles to monitor the physical environment, developing these tools for quantitative assessment of zooplankton and fish populations has lagged. However, newly developed active acoustic sensors, or echo sounders, for gliders make addressing these technological gaps now possible and promote a far more cost-effective approach than vessel-based sampling (Chave et al. 2018; Reiss et al. 2021). One such sensor, the Acoustic Zooplankton Fish Profiler (AZFP), is an autonomous, low-power echo sounder with significant internal storage and the capability to include up to four frequency channels (Chave et al. 2015). When integrated into a glider, it possesses the capabilities to study the abundance, distribution, and behavior of various sizes of fishes and/or zooplankton throughout the water column over large spatial scales by measuring acoustic backscatter returns with ultrasonic frequencies (Chave et al. 2018). Furthermore, multiple science sensors can operate simultaneously on a single glider, including acoustic receivers to support simultaneous telemetry efforts, and therefore connect the physical, biological, chemical, and geographical properties of the water column while observing horizontal and vertical distribution patterns of pelagic organisms. Recent successes have demonstrated the ability for these systems to augment and completely replace vessel-based surveys, in particular, the Conservation of Antarctic Marine Living Resources (CCAMLR) vessel-based surveys for the Antarctic krill fishery that were completely replaced by gliders equipped with AZFPs over a two-year time period (Reiss et al. 2021). These approaches work well in some Antarctic environments where krill scattering dominates the acoustic signal, but they will require a significant amount of ground truthing with traditional extractive approaches in areas including the Mid-Atlantic coastal shelf that are characterized by diverse zooplankton and fish taxa with overlapping scattering properties. We planned one, 3- to 4-week acoustic (AZFP) glider deployment during each phase of OW1 construction activities (preconstruction, during construction, and postconstruction) and timed to overlap with the bottom trawl, BRUV, and eDNA surveys. The survey path of the gliders constitutes multiple transects in and around the OW1 lease area, creating both latitudinal and longitudinal gradients in relation to turbine locations in estimated fish biomass (and other oceanographic parameters) during the different construction phases. As such, the glider survey efforts are most suitable for a BAG design.

2.8.4 | Acoustic Telemetry

Acoustic telemetry bridges invasive (catching and tagging) and noninvasive (subsequent detection) sampling and bridges scale. Most importantly, it integrates fish movement and oceanography at the regional scale to help disentangle fish responses to built structure and natural environmental forcing. An array of hydrophones monitors every estuarine inlet in New Jersey and integrates with neighboring states through a regional telemetry data sharing network, the Atlantic Cooperative Telemetry (ACT) Network, to track the along-shore migration of fishes that must cross electrical trunk lines of any coming array from any company, as well as onshore-offshore migration of estuarine-dependent species such as summer flounder identified by stakeholders to be of special concern due to their importance as a common and easily accessible fish for inshore anglers. This differs from the FMPs or supplemental/aligned efforts of other OSW projects in the MAB, in which receivers are clustered in high density within a lease to examine relatively small-scale habitat occupancy patterns. However, cooperation through ACT, when allowed by those companies, can address bight-wide use and migration patterns, including estuarine-ocean connection for other species, such as sandbar shark (*Carcharhinus plumbeus*). These hydrophone arrays and tags are compatible with those of offshore mobile hydrophones on AUVs (gliders), vessels, and moored arrays in place and planned for other OSW impact studies, as well as independent and unrelated studies (including those of the authors). Mobile hydrophones are deployed whenever vessels go out and for other sampling tasks and are deployed on trap lines for the structured habitat surveys. Thus, telemetry can be integrated with oceanographic study across scales from bight-wide to interturbine movement to test the effect of scale on the response of turbine extent and spacing.

3 | Conclusions

The spatial extent of OSW leases in the MAB, including BOEM Active Renewable Energy Leases, BOEM Wind Planning Areas, and BOEM Central Atlantic Draft Wind Energy Areas, approaches 20% of the continental shelf region between shore and the 100-m isobath (MARCO 2022). The footprint of actual turbines and their scour revetments (approximately 0.08% surface area for a 100-turbine development with a 10×10 nautical mile lease footprint given a 60-m diameter revetment per turbine) plus substations and buried cables within these is thus a tiny fraction. The margin of avoidance for captains fishing these, the region of wind stress abatement, and the ranging of foraging fish among and between them is intermediate in scale. The extent to which OSWs in the MAB will affect habitat and fisheries resources cannot be measured solely by their spatial extent but will depend on the mechanisms through which changes are imparted to the environment and fishing practices, which should be measured at scales both larger and smaller than OSW. These include substrate (Hutchison et al. 2020) and benthic community changes (Coolen et al. 2022), flow and turbulence, redistribution of bottom-tending fishing gear and recreational fishing practices bight-wide, and the perception of fish themselves regarding habitat value, habitat fractionation and connection, adjacent habitat proximity, and edge ratio that interacts with aspects of their life history. The extent of buildout for adjacent leases is not yet known and will remain in flux for years due to market forces, politics, and the involvement of several competing leaseholders. Likewise, the details of other installations themselves are yet unknown. Finally, the focus and design of FMPs for adjacent leases could change despite published guidelines and common review and permitting panels. However, there is no doubt that OSW development represents a large, regional-scale alteration of the marine ecosystem (see Miller 1986; Raffaelli and Moller 1999). The way to exploit these is to focus on experimental questions related to function and sampling designs on an encompassing theme, regional oceanography, and treating OSWs as manipulative treatments thereof. However, permitting generally requires empirical documentation of correlative changes, which can be related to managerial decisions on OSW extent, mitigation, and stakeholder compensation. We hope that the model we describe here can be considered and integrated through collaborative data sharing and effort. We need to approach the study of a single site as a model for any site and remain cognizant of its place and scale among neighboring leases. Data compatibility with existing surveys and a regional monitoring framework will become important. Data standards have been at the forefront of recent OSW working groups (Jenkins and Williams 2021), especially for fisheries research (ROSA 2021; ROSA 2022). The recent Federal Survey Mitigation Implementation Strategy from NOAA and BOEM identifies the need to "evaluate and integrate wind energy development monitoring studies with NOAA Fisheries surveys" (Hare et al. 2022). Our approach was designed to support this strategy by using survey methods that follow the federal standards, in using cooperative vessels and survey timing congruent to that in historic time series, and by calibrating novel sampling gear to allow integration into federal datasets. It also has utility as a global perspective on considerations of ecosystem impacts.

Author Contributions

Thomas Grothues: funding acquisition (lead), conceptualization (lead), project administration, writing – original draft preparation (equal), writing – review and editing (equal). **Jason Adolf:** funding acquisition (supporting), conceptualization (supporting), writing – original draft preparation (equal), writing – review and editing (equal). **Sarah Borsetti:** conceptualization (supporting), writing – original draft preparation (equal), writing – review and editing (equal). **Kaycee Coleman:** project administration (supporting), writing – original draft preparation (equal), visualization (lead). **Keith Dunton:** funding acquisition (supporting), conceptualization (supporting), writing – original draft preparation (equal), writing – review and editing (equal). **Josh Kohut:** funding acquisition (supporting), conceptualization (equal), writing – original draft preparation (equal), writing – review and editing (equal). **Daphne Munroe:** funding acquisition (supporting), project administration (supporting), conceptualization (supporting), writing – original draft preparation (equal), writing – review and editing (equal), visualization (supporting). **Shannon O'Leary:** conceptualization (supporting), writing (supporting) – original draft preparation (supporting), writing – review and editing (supporting). **Grace Saba:** funding acquisition (supporting), conceptualization (supporting), writing – original draft preparation (equal), writing – review and editing (equal). **Douglas Zemeckis:** funding acquisition (supporting), conceptualization (supporting), writing – original draft preparation (equal), writing – review and editing (equal), visualization (supporting).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Rutgers Offshore Wind Living Resources Studies at https://rowlrs.marine.rutgers.edu/data/.

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