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Quo Vadimus

Fisheries independent surveys in a new era of offshore wind energy development

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Abstract

Fisheries independent surveys require rethinking because of increasing spatial restrictions and interactions with offshore wind energy development (OWD). Fisheries, protected species, and environmental data collections have been conducted by scientific institutions to meet societal demands for food security, conservation, and other marine uses. These data collections provide information on key resource measures, essential for fisheries, protected species, and ecosystem management. With the increase in pace and magnitude of OWD's industrialization of marine waters, disruptions in these long-term time series can be expected. These disruptions will impact the ability to support current and future management goals and objectives. This paper presents an expert survey on the perceptions of OWD interactions with common survey designs and survey methodologies in Europe and the U.S., along with a selected sample of 75 fisheries independent surveys in the U.S. and Europe providing an initial assessment and description of potential impacts from OWD. About 72% of the surveys sampled record interactions with operational, planned or future OWD. Four case studies demonstrate efforts to address these interactions within European regions that have operational OWD and the U.S. where development has just begun. Finally, we make recommendations for future research important to continue meaningful scientific-based management advice.

Introduction

In order to address the impacts of climate change, many countries are increasing their commitments to decarbonizing their energy systems. This has resulted in a rapid increase in the planning and deployment of offshore wind energy development (OWD). Global OWD is expected to grow 10-fold and reach 519 GW by 2035 (WFO 2023). OWD in this paper is defined as the areas exposed to pre-construction geophysical and geotechnical surveys, construction, operation, and decommissioning activities; and includes all potential interactions with parts of the structures (e.g. turbines, cables) and associated infrastructure and operations (e.g. ports and vessels). The increase in pace, scale, and magnitude of OWD globally is expected to interact with marine ecosystems, including food resources such as fish and shellfish. Four broad types of OWD effects on fish and fisheries include artificial reef, fisheries exclusion, fisheries displacement, and energy landscape effects (Gill et al. 2020). The interactions between all phases of OWD and fisheries is a field of active research and a variety of impact producing effects have been observed and modeled that include: fisheries displacement, benthic and pelagic habitat alteration, fish and shellfish aggregation effects, electromagnetic fields interactions, oceanographic wind, and marine wake effects with potential to alter populations (Gill et al. 2020, Methratta et al. 2020, Hogan et al. 2023). These effects are in combination and compounded by other sources of human-induced environmental change such as climate change (Saba et al. 2023). While evidence is increasing on localized receptor responses to OWD effects, understanding stock and population level responses to these effects remain a gap in scientific understanding (Hogan et al. 2023). The disruption of fisheries independent surveys (i.e. standardized data collections in the field) is an emerging issue that has only recently been reported as a major concern with the increase in proposed OWD (BOEM 2021a,b, Hare et al. 2022, Haase et al. 2023, ICES 2023).

Fisheries independent surveys are essential for sustainably managing fisheries, wildlife, and ecosystems and are carried out by government agencies, intragovernmental bodies and nongovernmental organizations, universities and research centers. Many of these data collections are long-term time series that form the basis of accurate, precise, and timely science-based assessments and management advice for fisheries, protected species, and increased understanding and conservation of coastal and marine habitats and ecosystems. Survey programs rely on scientifically designed, standard methods to sample species at multiple sizes, life stages, locations, and time; and habitats (National Research Council 2000, Pennino et al. 2016). The accuracy of fish population assessments is greatly improved by high quality fisheries independent surveys conducted over long time periods (National Research Council 1998); therefore the management of fisheries populations for sustainable harvest is greatly improved for species with fisheries independent data (Gallo et al. 2022). Fisheries independent surveys rely on a variety of statistical survey designs (e.g. random stratified, fixed station, and transects) and survey gear methods (e.g. bottom trawls, dredges, hooks, acoustic methods, and traps) depending on the target species, habitat and assemblages. The standardization of these surveys and the consistent application of these designs and methods over time contribute to increased precision and reduced uncertainty necessary for effective marine resource management decision-making (Hare et al. 2022).

Fisheries independent surveys and OWD interactions

Fisheries independent survey methodologies and the platforms (vessels, uncrewed aerial and underwater vehicles, and aircraft) used to conduct them have been, and will be disrupted by OWD (Hare et al. 2022, Hogan et al. 2023). Disruptions to fisheries independent surveys from OWD are driven by four primary impacts, as described by Hare et al. (2022): (1) preclusion or exclusion, (2) impacts to survey designs, (3) alteration of habitat, and (4) reduced sampling productivity. Preclusion and exclusion occur when gear or vessels cannot be operated safely within an OWD or when permission to survey within the OWD is not granted. Areas that cannot be sampled from either legal or operational safety preclusions will result in reduced statistical power of the survey and often a violation of the survey design principles. Preclusion may require new sampling techniques to be used, which complicates the interpretation of relative trends in time series and, without suitable calibration studies, reduces the information the survey can provide for assessments. The issue of preclusion of survey activities due to the establishment of marine protected areas (MPAs) have demonstrated similar impacts. Alteration of benthic and pelagic habitats and airspace and specifically related to OWD can result in changes to species distributions, abundance, and vital rates (Cowan and Rose 2016, Hare et al. 2022, Buyse 2023, Hogan et al. 2023). This can result in differences in variance structure of biological measures between OWD and areas outside the influence of OWD (Hare et al. 2022). If unmonitored, stock changes due to habitat alteration could introduce bias in estimates of abundance and other biological measures. Lastly, OWD can introduce navigational impacts that reduce sampling productivity, increasing costs or reducing survey extent. For example, increasing vessel transit time can result in loss of allocated sea days used for sampling and thus lead to a decrease in the number of samples for a particular survey. For aerial surveys, turbine blade heights that exceed the elevation of cloud ceilings will preclude aerial survey operations from sampling from higher altitudes; and reduce the amount of time available to execute survey operations over time.

The impact on the fisheries independent surveys in the United States are reflected in environmental permitting documents, which designate the potential project-level and cumulative impacts on fisheries surveys as a major adverse impact. (BOEM 2021a,b). This designation was determined because "these impacts would require entities conducting surveys and scientific research to make significant investments to change methodologies to account for unsampleable areas, with potential long-term and irreversible impacts on fisheries and protected species research as a whole and the commercial fisheries community." (BOEM 2021b, p. 3–280). The ICES Workshop on Unavoidable Survey Effort Reduction 2 also describes the potential interactions of OWD on fisheries independent surveys (ICES 2023). The impacts of altered fisheries independent surveys have important consequences on fish population assessments. Spatial and temporal constraints on fisheries independent surveys lead to imprecise estimates of abundance and can alter the ability to measure all habitats and life stages of fish species, particularly if OWD overlaps with habitat areas that are unique to a given species' life history (Borsetti et al. 2023). For example, in the Cape Creus/Gulf of Roses in the Mediterranean Sea, an OWD has been designed in an area closed to trawl fisheries to allow hake stock to rebuild and where fisheries monitoring takes place (Sala-Coromina et al. 2021, Lloret et al. 2022). This is anticipated to affect the functionality of this closed area as well as the implementation of scientific monitoring there and may be affected by future OWD (Lloret et al. 2022). Advances in spatially explicit predictive models are being made and are needed for more effective spatial fisheries management to allow scientists and managers to respond to changes in fishery ecosystems (Mackinson 2001). The spatial data gaps created by OWD will make the development of these spatial models very challenging. Disruption of long-term monitoring programs that reduce the accuracy, precision, and timeliness of data used for management can have profound negative impacts on the sustainable management of these resources with socio-economic consequences on impacted communities. Despite the potential deleterious impacts of OWD on recurring fisheries independent surveys and the knock-on effects on population assessments and other advice, these impacts can be mitigated by advancing new survey designs, and advanced sampling methods, such as remote-sampling (optical, acoustic) or fixed-gear survey methods, that are compatible with offshore energy development.

The objectives of this article are to (1) raise awareness of interactions between fisheries independent surveys and OWD, (2) collate insights and recommendations from experts, and (3) illustrate impacts and mitigation strategies with case studies and inventories. We present this information so that the scientific community can take proactive measures to better understand the interactions of existing and planned OWD on fisheries independent surveys; and develop common approaches to mitigate the impacts with the goal common to all recurring long-term survey efforts to provide timely, high-quality data that support assessments and sustainable management of marine resources in the context of evolving ocean uses.

Methods

The authors developed multiple methods to describe and begin to assess the interactions of fisheries independent surveys and OWD. These methods included a survey of experts within the ICES community, information gathering on interactions for a selected sample of fisheries independent surveys, and case studies demonstrating efforts to address interactions.

An expert survey of 29 ICES working group chairs across 18 working groups was conducted in the spring of 2021 on perceptions by scientists on OWD and fisheries independent survey interactions. The purpose was to better understand if and how fisheries experts are addressing the effects of OWD on the design and methods of established resource and fisheries monitoring programs. The author's selected ICES expert working groups because ICES represents one of the longest serving and largest intergovernmental bodies for fisheries science and management with active participation of fisheries independent survey experts (ICES 2019). Respondents were affiliated with government, academic, and private institutions. The survey protocol consisted of 18 close-ended questions with three open-ended responses that allowed participants to expand on known efforts to address OWD and fisheries independent survey interactions. The questions gathered perceptions of the importance of effects on fisheries data collections, assessments and management advice using a 5-point Likert scale (Likert 1932) and a series of Yes/No/I don't know questions, where "I don't know" was selected if the respondent was uncertain if there are or would be impacts. Likert scale questions were scored on a scale of 1–5 with (1) not important, (2) slightly important, (3) moderately important, (4) important, and (5) very important. Researchers used open source Mentimeter's Interactive Survey Maker program, which allows the public to respond to shared surveys and responses are automatically populated in a downloadable spreadsheet with Basic version (Mentimeter 2022). The survey was sent via email to ICES chairs and respondents had three weeks to respond.

Building on the survey, the authors selected and inventoried a sample of long-term fisheries independent surveys. The inventory began with authors collating information on fisheries independent surveys within their networks, this involved contacting survey experts and desktop searches of publicly available reports, scientific publications, and web content. The snowball search technique was used to expand searches as well as reach out to survey leads where information was not publicly accessible (Wohlin et al. 2022). Authors recorded those surveys that met the definition of fisheries independent surveys in areas of existing and proposed OWD, primarily within the U.S., Spanish Mediterranean Sea, Baltic Sea and the United Kingdom EEZ (Exclusive economic zone). The inventory does not represent all surveys in each region where OWD is proposed. Survey information collected included the type of data collected, geographic area sampled, year the survey commenced, frequency of the survey, survey methodology and the application of the survey data collected. For each, information was collected on whether there was known interaction with OWD, potential impacts on sampling methods, statistical design, and habitat alterations that could impact ability to offer scientific advice. Each identified survey was evaluated to determine if there were any peer reviewed publications or grey literature that documented any analysis completed that assessed interactions with OWD. Any identified activities to address these impacts were also included in the inventory based on evaluation of publicly available reports or scientific publications and conversations with survey experts. See supplementary material for complete inventory.

Case study examples were selected based on findings from developing the inventory and where possible evidence through scientific publications or published reports that documented efforts to address the issue of OWD and fisheries independent survey interactions. The case studies were also selected to contrast the approaches used in Europe and the U.S. and the long-term global effect that the absence of guidance and regulation to address impacts to fisheries independent surveys can have as new projects continue to be proposed. Finally, based on the results of the analyses, authors identify gaps and recommendations for scientists, cooperative research partners, fisheries managers, and the greater fisheries community who are either responsible for the design and execution of fisheries data collections or depend on these data for assessments or decision-making.

Results

Survey of ICES expert working group chairs

The survey was sent to ICES chairs of each working group ($n = 31$) under the Ecosystem Observation Steering Group.

A total of 29 chairs responded to the survey. When asked if respondents believed existing and proposed OWD has the potential to interact with fisheries independent surveys, 85% chose "Moderate," "Important" or "Very Important." Fig. 2 shows results for a set of questions regarding three of the four primary OWD and fisheries independent survey impact categories outlined in Section 2 and described in Hare et al. (2022); these include the impacts due to (1) preclusion, (2) statistical design, and (3) habitat alterations. The survey highlights the uncertainty in the effects, as the majority of respondents did not know if existing sampling methods (question 1a, 58%) and statistical designs (question 2a, 69%) would be compatible with OWD and 42% (question 3a) did not know if surveys can account for biological or habitat changes without modification. Despite the uncertainty, as shown in Fig. 2, very few respondents answered "Yes" for all three of the impact categories, meaning there are few instances where preclusion, statistical design and habitat alterations are not considered a concern. The majority believed the effects to be important by ranking moderately important or higher: (1b) preclusion (76%), (2b) statistical design (84%), and (3b) habitat alterations (90%). None of the respondents perceived these impacts to be "not important."

Findings of the ICES expert survey highlighted notable uncertainty internationally on the effects of OWD but high levels of the importance to understand and address these effects.

Inventory of fisheries independent survey data collections

A total of 75 fisheries independent surveys were selected and inventoried. The inventory covers waters in the U.S., Spanish Mediterranean Sea, Baltic Sea- Germany EEZ and the United Kingdom EEZ. Results show that some surveys are already overlapping with current OWD, including offshore wind energy leases and planning areas. Of the 75 surveys included in the inventory, 54 (74%) interact with operational, planned, or future OWD (Table 1).

The data collected showed that fisheries independent surveys are conducted at varying frequencies and using varied designs, and methodologies. Most of the surveys collect biological data, e.g. abundance and biomass of marine species, which contribute to the assessments of fish and shellfish stocks but are also used to support the assessment of wildlife species with

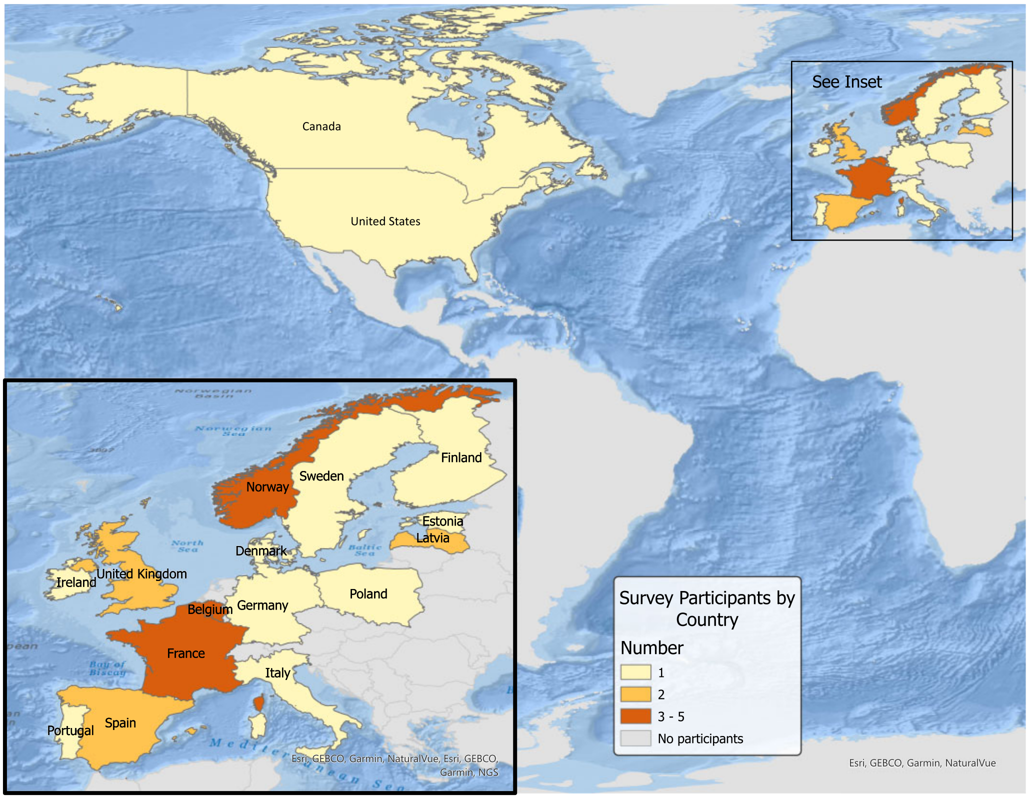

Figure 1. The number of survey participants by country.

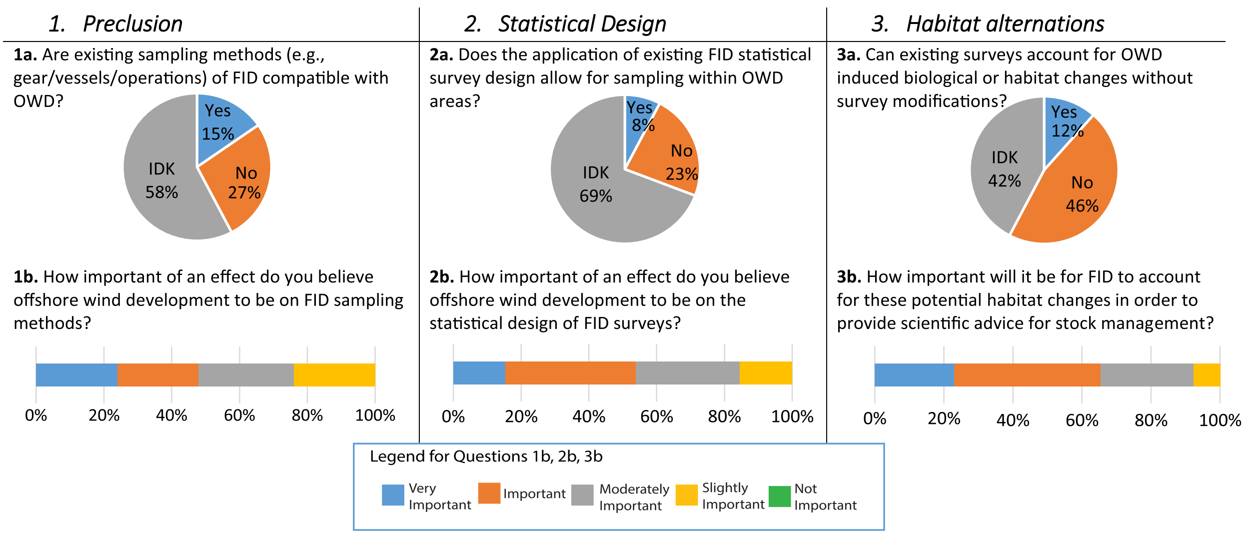

Figure 2. The ICES expert chairs' perceptions of OWD effects on scientific surveys in three impact categories (FID: "Fishery Independent Data"; IDK= "I don't know"; OWD: "Offshore wind energy development").

special management designations such as protected species in the U.S. Of the 54 fisheries independent surveys that overlap with existing and proposed OWD, 56% ($N = 30$) cannot and 41% ($N = 22$) are unknown if they can operate within the OWD area without modification. For those that do overlap, 24% were identified as not compatible with OWD without modification to statistical survey design. The fixed station design methodology is common in the U.S. and European international surveys. The sample data collected has shown that there is a compelling impact on fixed station surveys that overlap with OWD. For example, all countries that contribute toward the internationally coordinated North Sea International Bottom Trawl Survey (NS-IBTS) have been impacted by the presence of OWD; the survey samples each ICES statistical rectangle twice, with two different vessels/countries (ICES 2020b). One of the contributing surveys is the IBTS3e otter trawl survey in ICES areas 4a- c of the North Sea, due to OWD in the region survey sites have had to be relocated to avoid overlap (Fig. 3). However, with the significant expansion of OWD in the North Sea, there is uncertainty on how

Table 1. Summary of the effects of OWD by number of fisheries independent survey collections. Categories marked with a ∗ do not equal 54 as one survey was not applicable

	Yes N (%)	No N (%)	Unknown N (%)
Does scientific survey overlap with OWD?	54 (74%)	17 (23%)	2 (3%)
For scientific surveys that do overlap with OWD (N = 54):			
Preclusion factors *Can survey sample within OWD without modification of survey?*	2 (4%)	30 (56%)	22 (41%)
Violation of survey design∗ *Is survey statistical design compatible with OWD without modification of survey?*	12 (22%)	13 (24%)	28 (52%)
Habitat change∗ *Are differences in variance structure accounted for and monitored inside and outside OWD?*	1 (2%)	19 (35%)	33 (61%)
Loss of efficiency *Does OWD lead to increased transit or other impacts that may limit sea days for survey sampling?*	10 (19%)	11 (20%)	33 (61%)
Are there activities to address survey impacts from OWD?	27 (50%)	5 (9%)	22 (41%)
Is survey capable of detecting how OWD is affecting fisheries (habitat, stock, populations)?	4 (7%)	11 (20%)	39 (72%)

Categories marked with a ∗ do not equal 54 as one survey was not applicable.

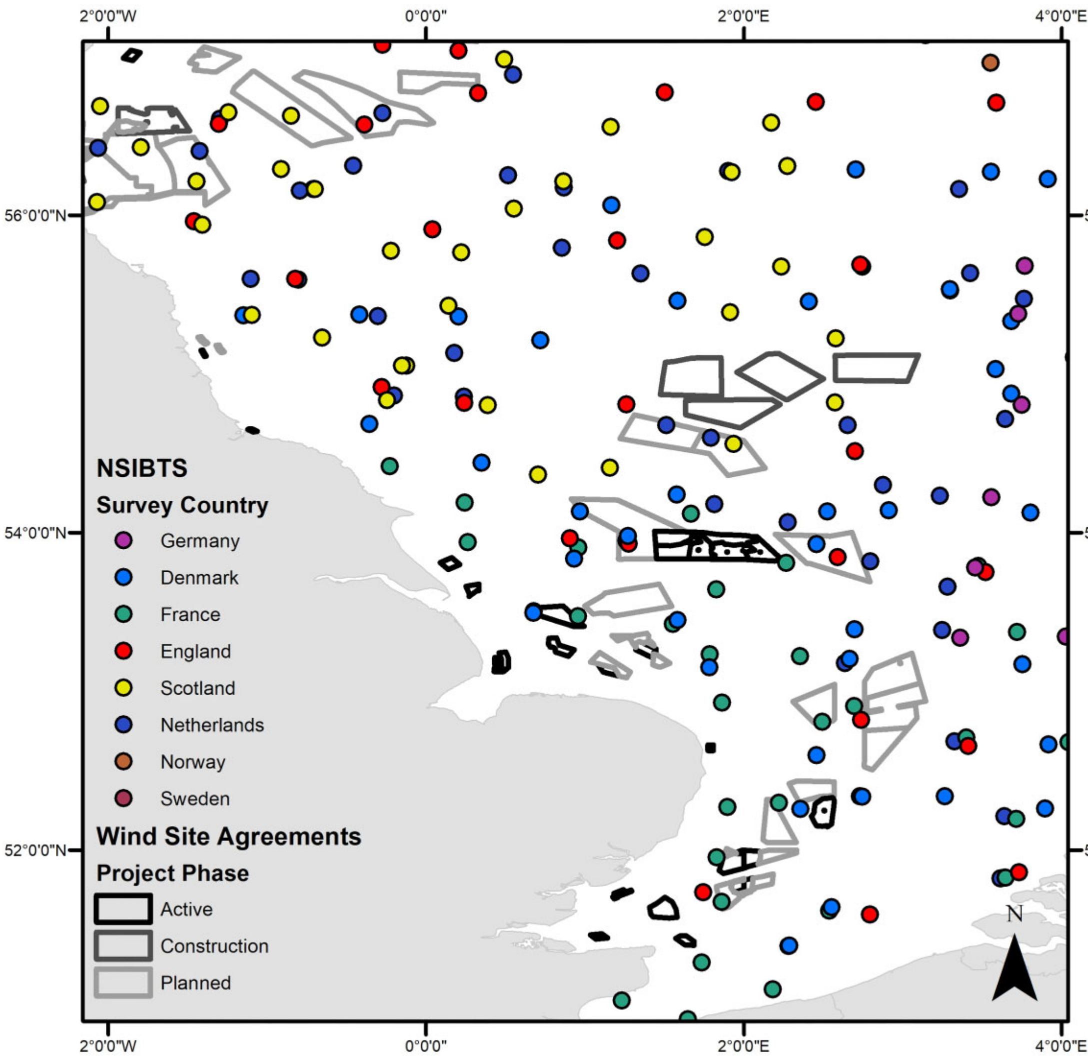

Figure 3. Approximate haul locations from NS-IBTS 2022 survey, by nationality of survey vessel, and the outline of OWD, by project phase. Wind Site Agreements (The Crown Estate 2023). Contains data provided by The Crown Estate that is protected by copyright and database rights; Crown Estate Scotland 2023. Contains public sector information, licensed under the Open Government Licence v3.0, from Crown Estate Scotland), North Sea International Bottom Trawl Survey (DATRAS 2023c).

those geographical changes will affect the data collected and if there will be changes in the long-time series for fish data.

In the U.S. Northeast EEZ, the use of random stratified design was the most common sampling design. The U.S. Northeast EEZ Atlantic Scallop Survey had considerable overlap with survey strata experiencing up to 100% overlap with existing lease and proposed OWD. The Atlantic Scallop fishery is the second most valued fishery in the United States (NMFS 2023). All recorded line transect surveys were conducted by the U.S., and overlap with OWD. Both the North Atlantic Right Whale Aerial Survey and the Marine Mammals and Sea Turtle ship-based and aerial surveys, conducted by NEFSC, will require new designs and possible survey methodology changes due to overlap with OWD and the associated impacts of preclusion, habitat change, and loss of efficiency.

The inventory also summarizes how OWD will affect the survey's efficiency; all surveys in the Baltic Sea, where there is significant existing and proposed OWD, report a loss of efficiency. In contrast, the U.S. South Atlantic EEZ does not, where minimal OWD is proposed. The majority of surveys are unknown (61%). Increased transit times can result in less time to complete sampling stations and also increase fuel consumption leading to reduced sampling power, increased fuel costs, and potentially increased vessel emissions.

For 72% of surveys, it was unknown whether OWD would violate survey design assumptions. Removing large areas from survey domains and assuming abundance, distribution, and vital rates are the same inside these areas as outside these areas is a relatively untested assumption. Violation of this assumption has the potential to increase uncertainty in the status of populations.

Case studies

OWD has been in operation in European waters, but there is a relatively advanced level of progression, especially in the Baltic Sea and the United Kingdom EEZ waters. Two case studies are presented below to demonstrate the impact on fisheries independent survey areas in these regions and the implications of uncertainty as OWD is rapidly expanding. In the U.S. the first two commercial scale OWDs are expected to be in full operation by 2024. However, survey strata for U.S. Northeast EEZ multi-species bottom trawl survey are already being impacted by construction and cable laying activities, requiring survey leads to identify alternative sampling locations. Two additional case studies are presented below on efforts in the U.S. to develop a strategy for fisheries independent survey mitigation and research methods to address interactions.

Case study 1: a framework in the Northeastern United States for evaluating and mitigating OWD impacts on scientific surveys

In U.S. waters, development activities are at an earlier stage, and interactions with fisheries independent survey programs vary regionally. Overlap on the U.S. continental Northeast Atlantic (Fig. 4) is relatively more substantial, with proposed development in other areas, including: Gulf of Mexico, Southeast Atlantic, Pacific and Hawaii (Supplementary Figures S1-S4). The U.S. has developed a national strategy that identifies and describes the issue of survey disruptions; and establishes goals, objectives and near-term and long-term actions to advance solutions to mitigate the impacts of OWD on their scientific survey enterprise (Hare et al. 2022).

During the analysis of impacts to NOAA Fisheries surveys from the first commercial scale OWD in the U.S., NOAA scientists and the Bureau of Ocean Energy Management (BOEM) OWD regulatory experts discussed mechanisms and steps that could be evaluated in the environmental assessment to address both project-level and regional- level cumulative effects from the Vineyard Wind 1 development (BOEM 2021b). These discussions led to the development of the strategy that is described in Hare et al. (2022), and includes the following six elements:

1. Evaluate and quantify the effects and impacts.
2. Evaluate or develop appropriate statistical designs, sampling protocols, and methods.
3. Calibrate and or integrate existing and new survey approaches.
4. Develop additional interim indices.
5. Implement new sampling methods over time.
6. Develop and communicate new regional data streams.

This methodological framework is now being applied to affected U.S. federal fisheries surveys that are carried out in the U.S. Northeast EEZ. Individual survey mitigation plans will be drafted that describe how the survey may be impacted by each of the four described impact effects (preclusion, statistical design, habitat change, and loss of sampling efficiency). Based on this analysis, survey plans will also include details for each of the six mitigation elements. These and other details will form the basis for a Northeast survey mitigation program that can have broader application to surveys in other regions. Efforts are underway to complete these plans and the program in the Northeast Region where the first commercial-scale OWD is now under construction. While this strategy is focused on the U.S. Northeast EEZ, many if not all aspects of the strategy are applicable to other geographic regions. NOAA Fisheries Southwest and Northwest Regions in the Pacific Ocean and NOAA Fisheries Southeast Region, inclusive of the Southwest Atlantic and the Gulf of Mexico, are currently in development of analogous survey mitigation strategies, programs, and survey specific mitigation plans. Each of these federal fisheries independent surveys in the U.S. were inventoried in Supplementary Tables S1–S4.

Case study 2: methods to evaluate and quantify impacts on the U.S. Northeast EEZ bottom trawl survey

In the U.S. Northeast EEZ waters from North Carolina to Nova Scotia, NOAA Fisheries conducts a fishery independent, stratified random, multispecies bottom trawl survey to collect data used in ecosystem reports and in stock assessments for ~40 demersal fish species (Fig. 4). The survey has used standardized and calibrated methods since 1963 (fall survey) and 1968 (spring survey). The survey utilizes a 63 m research vessel, which is not expected to be able to safely tow gear within OWD. Some strata are projected to have up to 76% of their area developed for OWD. The highest priority concern is the issue of preclusion and the loss of stations and how that will impact indices of abundance and the uncertainty around those estimates. Other concerns include how OWD will impact the survey's integrity including changing species spatial and

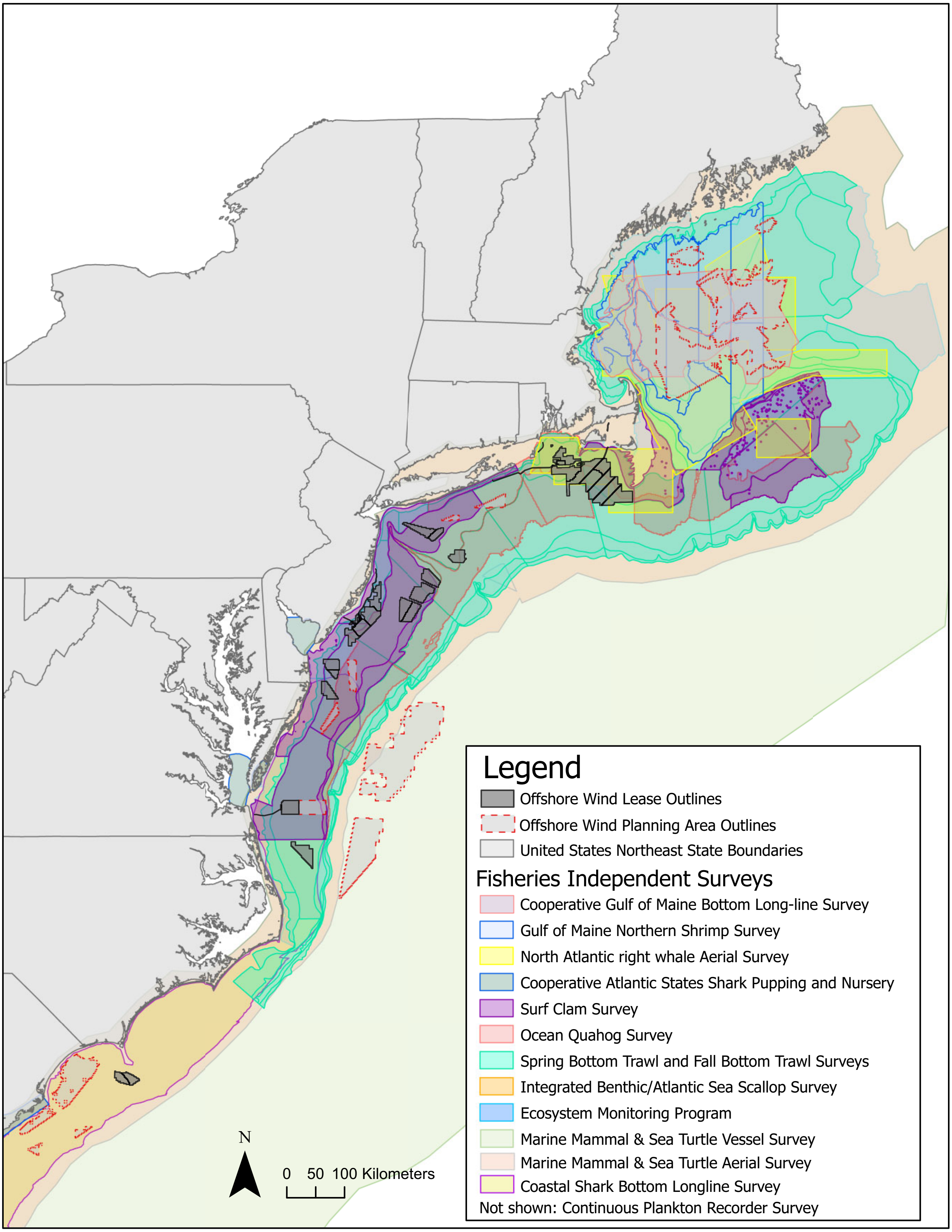

Figure 4. OWD and NOAA Fisheries Surveys in the United States Northeast EEZ. Figure demonstrates the interactions of nine scientific surveys conducted in the Northeast region with lease and planning areas for OWD.

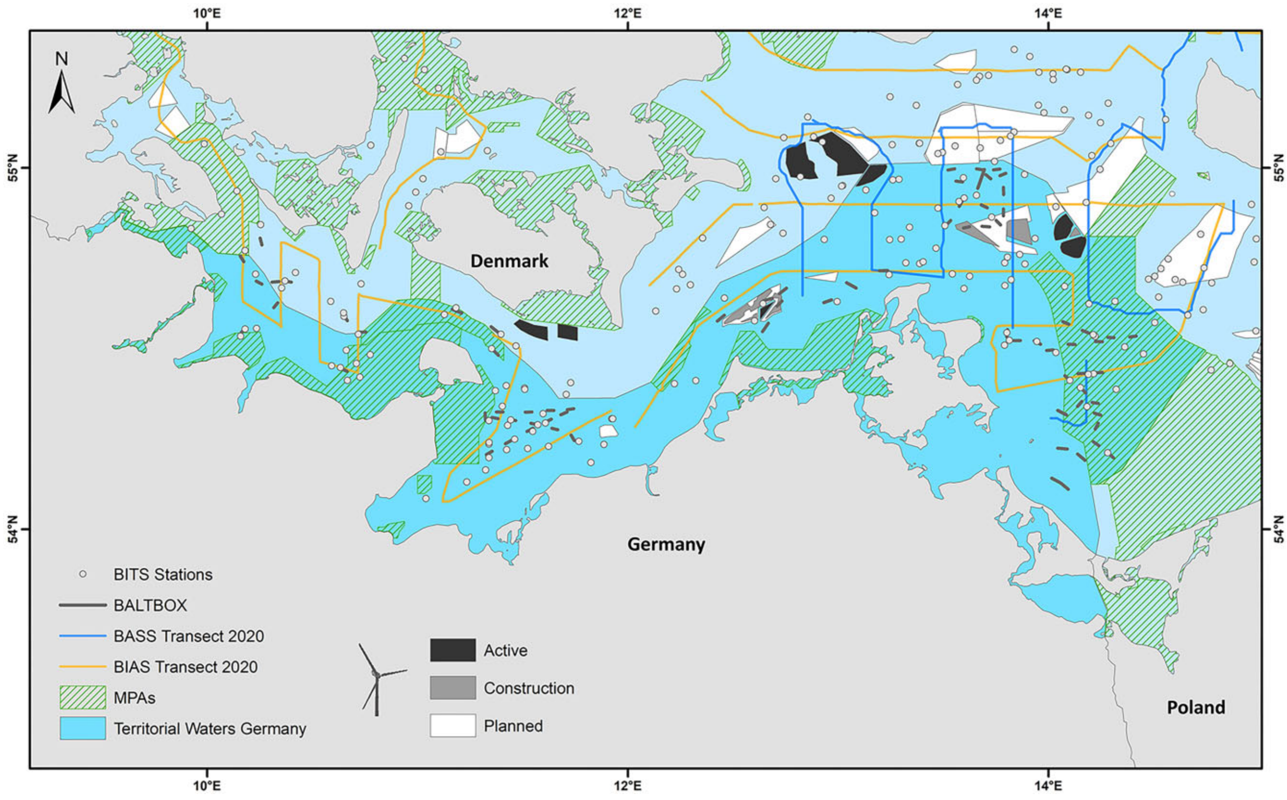

Figure 5. Current state of OWD and surveys in the Baltic Sea EEZ of Germany including NATURA 2000 MPAs. Active: OWD that are currently active or fully commissioned; construction: preconstruction, consent authorized; planned: concept/early planning, development zone, consent application submitted; BASS (ICES Baltic Acoustic Spring Survey), BIAS (ICES Baltic International Acoustic Survey), BITS (ICES Baltic International Trawl Survey), BALTBOX (German Trawl Survey Baltic Box), MPA: Marine Protected Areas.

temporal distributions and potential transition to different vessels and gear types with varying catchability.

To address these conflicts, the government-funded, multi-institutional partnership Survey Simulation Experimentation and Evaluation Project (SSEEP), is building a simulation modeling framework to quantitatively assess the impact of a changing survey footprint on the quality of survey data products, explore the differential impacts on individual species and species groups, and compare survey design options to minimize the uncertainty of abundance estimates for managed fish species of commercial importance (Fay et al. 2023). A steering committee of subject matter experts from government, academia, and non-profit institutions provides oversight. In its first year, the project team facilitated stakeholder workshops to receive input from affected fishermen, scientists, and data users to define the key capabilities of the model and co-produce primary questions to explore with the model. The project will produce a simulation environment that can assess how to best respond to survey effort reductions and consider optimization of station selection, related to efforts ongoing within the Workshop on Unavoidable Survey Effort Reduction (ICES 2020a & 2023) and informed by survey optimization methods being explored on the United States west coast (e.g. Oyafuso et al. 2022, von Szalay et al. 2023, Bryan and Thorson 2023). This project will ultimately inform efforts to redesign the multispecies bottom trawl survey while ensuring the continuity of the survey time series and limiting uncertainty in abundance estimates.

Case study 3: OWD in the German EEZ, Baltic Sea

With its mostly shallow bathymetry and long coastline, the Baltic Sea brings many opportunities for setting up OWD. The German Baltic EEZ has an area of around 4 452 km^2 and has generated ca. 1.1 GW through OWD by the end of 2022. To achieve the German goal (North Sea and Baltic Sea combined) of 40 GW green energy production, the number of areas allocated for OWD in the Baltic is increasing (Fig. 5). In the Baltic, Germany conducts three ICES-coordinated fisheries independent surveys in their EEZ: the demersal Baltic International Trawl Survey (BITS), and the two hydroacoustic surveys Baltic Acoustic Spring Survey (BASS) and Baltic International Acoustic Survey (BIAS). These surveys are of high priority and contribute to the survey index for the stock assessment of commercially exploited fish stocks (for more information see ICES 2017a, b). The acoustic transects of the BASS and BIAS are similar each year and pelagic trawling is conducted based on fish echo. To date, the hydroacoustic tracks are modified when they would intersect an OWD, because fisheries research with its standardized fishing methods is prohibited within OWD. Pelagic trawl stations are therefore also only conducted outside OWD. Until now, track changes associated with detouring OWD did not affect the surveys negatively. Additional OWD might, however, lead to further track modifications, increased steaming times and as a result a reduction in the total surveyed area.

The BITS stations are monitored randomly but depth-stratified. During the selection process, stations that overlap with OWD are excluded and a new station from the same depth strata is chosen. An increase in steaming time between stations due to OWD has not affected the survey success but could become an issue in the future. The effect of station losses on the stock indices has not been assessed quantitatively.

Further, there are several national surveys of various importance conducted within the German EEZ. As an example, the BaltBox survey has fixed fishing stations to investigate biodiversity over time. The survey provides data for the HELCOM Red List of Baltic Sea species in danger of becoming extinct and thus also for the European Union EU Marine Strategy Framework Directive. In the case of fixed stations, reference stations should be identified and established to avoid a break in the time-series.

For the German EEZ, OWD in combination with some of the MPAs will continue to exclude mobile bottom contacting gears in the near future so that additional fishing areas will be excluded from the BITS and BaltBox survey.

Case study 4: interactions between OWD and fisheries in the North Sea-United Kingdom EEZ

The UK has significantly increased OWD in its waters with an ambitious target to increase OWD fivefold to 50 GW by 2030 (UK Government 2022). Continuing fisheries independent surveys is becoming more problematic as OWD increases. To date, many UK OWD is relatively close to shore in areas with limited overlap between fisheries independent surveys. In many instances where overlap occurs, survey stations have been relocated to offset this issue. Interactions are expected to increase as OWD moves further offshore into areas where fisheries independent surveys are conducted. There are increased challenges for data collection, as the current methods are not compatible with OWD, meaning adaptation is needed where survey strata and OWD overlap. Anecdotal information suggests that data collection and monitoring activities in the Moray Firth, northeast Scotland, is hampered by the presence of OWD. Alternative methods are currently being investigated instead of traditional approaches (e.g. pelagic gears), for example the use of remotely operated vehicles (ROVs), autonomous or sail drones, to cover those areas and maintain the collection of important data that feeds into stock assessments. Despite the promise of these approaches in other systems (e.g. De Robertis et al. 2021), their effectiveness in replacing ship-based surveys may be limited by their inability to collect biological samples (e.g. Bolser et al. 2023) and the alteration to methodology may affect interpretation of trends in long standing time series data.

In the North Sea there are further challenges due to the complex legislative framework between devolved administrations within the UK, and also between the UK and EU. For example, the Dogger Bank is a large sandbank in a shallow area of the North Sea and provides habitats for a wide range of fish species, including sandeels. This is an area of large-scale OWD, currently in differing phases, and likely to have extensive overlap with fisheries independent surveys, for example an important sandeel survey (Fig. 6). Sandeels are highlighted within the Environmental Statements for current Dogger Bank developments (Royal Haskoning DHV 2014), as a species of concern due to their importance for bird populations in the area. Continued monitoring is therefore important for management of the wider ecosystem. There is currently no publicly available evidence of a strategy within the UK to assess the impacts of large scale OWD on fisheries independent surveys in this region. A holistic strategy to mitigate impacts on fish (and shellfish) population monitoring activities and wider environmental surveys should be carefully considered to ensure the continuation of data collection that provide evidence-based information to policy and management.

Discussion

Our inventory highlighted 54 surveys (out of 75, i.e. 72% of the total) that interact with OWD and results show that much is still unknown about how surveys will be disrupted and the impact of these disruptions on stock assessments. Although the inventory in this article represents a selected sample and is not exhaustive of all fisheries independent surveys globally, results are likely to be representative of conditions that are similar in many other areas globally. Our findings indicated that the majority of fisheries independent surveys that interact with OWD will be disrupted (e.g. preclusion or exclusion, impacts to survey designs, alteration of habitat, and reduced sampling productivity) posing serious challenges to monitoring and stock assessments in the future. The inventory highlights the need to more comprehensively inventory and assess the interactions between OWD and fisheries independent surveys to help understand the effect on data collections and stock assessments; and to report and evaluate the mitigation measures and approaches that are being advanced to address the impacts of OWD on fisheries independent surveys.

A common thread across the analyses in this article is the need to include interactions of OWD with fisheries independent surveys and knock-on impacts on assessments of stocks and scientific advice in primary research. Although OWD has occurred for decades in the shallower waters of the North Sea, the issue of fisheries independent surveys has only recently been given attention (Methratta et al. 2020, 2023, ICES 2023). As described in the European case studies, disruption of fisheries independent surveys by spatial overlap of OWD can be compounded by the designation of MPAs, many of which are part of the Natura 2000—the ecological network of protected sites for selected habitats and species within the EU, depending on the conservation objectives that are prescribed, i.e. excluding the use of bottom-tending sampling gear. In combination with OWD, any imposed spatial exclusions may also constrain the use of traditional scientific survey methods and designs. Similar to habitat alteration due to OWD effects, MPAs may also result in changes in population distribution, abundance, and vital rates that if unaccounted for in survey and assessment methods could introduce biases in accurately and precisely measuring population status. If the establishment of MPAs require changes in existing survey methods and platforms, the solutions required to adopt new survey methods may share very similar mitigation responses as the responses the scientific community may need to address OWD impacts. Similarly, changes in ocean temperature, pH, circulation and productivity from climate change can also alter marine ecosystems. These changes include marine species distribution, abundance, productivity, predator-prey interactions, growth rates and more (Perry et al. 2005, Hare et al. 2007, Pinsky et al. 2020, Pankhurst and Munday 2011, Petitgas et al. 2012, Oesterwind et al. 2022). Effects on fishery landings and fishing effort due to climate change have also been studied (Pinsky and Fogarty 2012, Gamito et al. 2015, Albo-Puigserver et al. 2022, Smith et al., 2023). Although useful lessons can be applied from approaches to monitor the

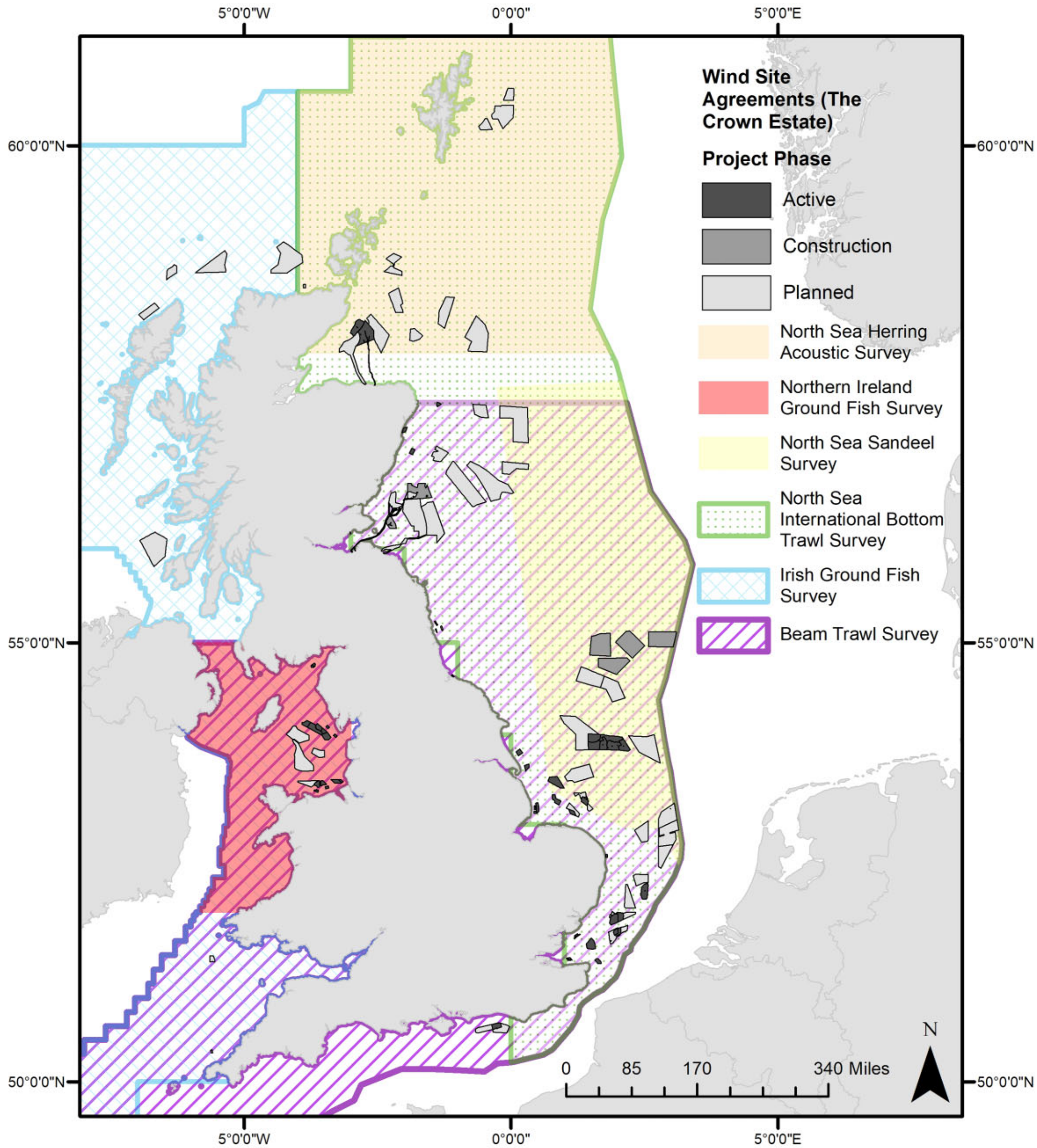

Figure 6. Current state of OWD and overlap with selected fisheries independent surveys within the UK EEZ. Active: OWD that are currently active or fully commissioned; construction: preconstruction, under construction; planned: consented, pre-lanning application, in planning. This does not illustrate all surveys in UK waters nor does it also depict survey exclusion areas due to MPAs. Wind Site Agreements (The Crown Estate 2023). Contains data provided by The Crown Estate that is protected by copyright and database rights; Crown Estate Scotland 2023. Contains public sector information, licensed under the Open Government Licence v3.0, from Crown Estate Scotland), North Sea Herring Acoustic Survey (Medin 2023), Northern Ireland Ground Fish Survey (DATRAS 2023a), North Sea Sandeel Survey (DATRAS 2023b), North Sea International Bottom Trawl Survey (ICES 2020b), Irish Ground Fish Survey (part of IBTS internationally coordinated survey) (ICES 2017c), Beam Trawl Survey (ICES 2019).

status of habitats and species changing in response to climate change, the survey issues associated with OWD, such as the issue of preclusion, can be quite different. While changing environmental conditions from climate change may challenge existing observation systems, e.g. observation availability due to changes in migration or range expansions and contractions, these changes do not preclude our ability to sample them with existing methods and designs.

Evident from the results of this paper, developing strategies to inventory, analyze, and mitigate the impacts of OWD on fisheries independent surveys is necessary across all regions experiencing rapid and large-scale OWD. While some regions in the U.S. have completed mitigation strategies, the development of survey specific mitigation plans and programs have not yet occurred. In Europe, there is no publicly available evidence that survey mitigation strategies have been initiated to date although early efforts to understand these interactions, as reported for the German EEZ case study, are beginning to take shape. Research gaps exist to better describe, analyze, and develop solutions to the four types of impacts to scientific surveys and advice. Primary among these research gaps is ensuring that effective monitoring programs are in place to characterize how populations of managed species will respond to large-scale habitat change. From a fisheries and population dynamics perspective, the effects that have the highest potential to alter distribution, abundance, and vital rates are critical to monitor. For example, if structure-oriented fish aggregate in OWD and either experience increased mortality or increased productivity and these areas are unmonitored; scientists and managers will be unaware of these changes in stock condition, which may have impacts both on the resource and fishing communities. Various existing publications outline these habitat related research gaps; however, few programs have been developed successfully to measure these effects at the population and ecosystem scales (Methratta et al. 2020, 2023).

Another finding common to examples presented in this paper is the need to develop and operationalize the necessary survey designs and sampling approaches and methods that will be necessary to mitigate OWD impacts. Where they are not currently being implemented, there remains a need to explore the use of and integrate remote sampling methods (e.g. active and passive acoustics, underwater optics, telemetry, and eDNA) into existing time series in OWD via calibration with current methods (e.g. Hammerl et al. 2024). The same is true for augmentation of fisheries independent survey sampling programs with cooperative fisheries sampling. In both cases, implementing new sampling modalities will come with non-trivial data management needs that must be addressed, and a need to employ estimation methods capable of handling data from multiple sources and/or "unbalanced" sampling (e.g. model-based methods; Alglave et al. 2022, O'Leary et al. 2022, Grüss et al. 2023). Frameworks exist to help scientists in designing and integrating more flexible survey designs and approaches to meet our societal management objective (ICES 2023). These flexible survey designs can be used to address issues in unavoidable effort reduction due to fishing gear conflicts, untrawlable habitats, or changes in habitats such as due to OWD. Decision-support systems need to be developed to allow scientists, managers, and resource users to design and implement new scientific approaches to our data collections and assessments. Applying these flexible survey programs to address OWD interactions in combination with other impacts on our observation systems, such as lost sea days, changes in survey frames due to climate change; and to continue to provide precise, accurate, and timely scientific advice is urgently needed. Finally, a major operational research gap exists in testing these technologies and applying them to expanding OWD. This includes establishing the potential to increase and expand new observation systems and to leverage the infrastructure of thousands of kilometers of submarine cables and tens of thousands of offshore energy platforms that will have power, data transmission, and associated operations and maintenance across the entire system.

Recommendations

The 2023 *Workshop on a Research Roadmap for Offshore and Marine Renewable Energy* outlines a call for scientific action by ICES and ICES member countries to address the immediate challenges and opportunities associated with large scale marine renewable industrialization (ICES 2023). The future development of a research road map that is outlined in this report includes the issue of OWD on fisheries data collections. This roadmap or similar strategies is urgently needed. While some countries have begun developing strategies to mitigate the impacts of OWD on scientific surveys and advice, sharing lessons learned across geographic regions will be essential as fisheries scientific and management bodies will need to better understand these interactions and develop region-specific survey mitigation and research plans. As the U.S. is beginning to implement and develop survey mitigation strategies, programs, and survey specific mitigation plans; these strategies can also be developed in other regions. For example the EU could address potential impacts of OWD on member states fisheries' scientific surveys within the Data Collection Framework (DCF), as NOAA Fisheries and BOEM have done recently. An EU Survey Mitigation Strategy could be drawn to responsibly advance OWD and address scientific survey needs. The five goals of the EU strategy could adapt on those of the US, acknowledging that in order to achieve these goals they must be coordinated with neighboring coastal states:

- (i) mitigate impacts of OWD on fisheries surveys;
- (ii) evaluate and integrate, where feasible, OWD monitoring studies with fisheries surveys;
- (iii) collaboratively plan and implement fisheries survey mitigation with partners, stakeholders, and other ocean users using the principles of best scientific information available and co-production of knowledge, including fishermen's local ecological knowledge;
- (iv) adaptively implement this 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
- (v) advance coordination between EU member states and ICES in the execution of this strategy and share experiences and lessons learned with other regions and countries where OWD is being planned and underway.

In addition to the recommendation of developing overarching national, and regional mitigation strategies, programs, and plans; authors of this paper suggest the following recommendations based on the findings of this study and case studies presented. These recommendations are suitable for implementation in the ICES context but could be enforced elsewhere in the context of other research institutions or other regional fishery management organizations:

1. Complete an inventory and evaluation of fisheries independent surveys that are, or will be, impacted by existing or proposed OWD (see for example Haase et al. 2023 for the Baltic Sea); and leverage existing data and communications to establish web-based portal(s) for conveying this information.
2. Inventory and conduct research on the interactions of OWD on fisheries dependent data collections. Fisheries dependent data is data derived from fishing activities (i.e. vessel logbooks, observer data, and vessel monitoring systems). Displacement of fishing vessels from OWD could affect the time series of these data sources and their use in fisheries management.
3. Design, apply, and report out on standard methodologies for evaluating risks or impacts to the surveys, such as described in Case Study #2
4. Communicate and report on statistical and sampling methods and approaches for mitigating impacts to fisheries data collections

   a. Using a common lens of performance, evaluate and report current approaches and survey mitigation success/evaluations
   b. Consider establishing transboundary/transnational set of performance metrics
5. Develop standards and regional guidance that improves applicability of environmental monitoring conducted where there are overlaps with OWD for fish population assessments, including collaborative knowledge coproduction as a guiding principle.
6. Create or use existing tools to test how changes in data collections affect stock advice and management, e.g. through simulation modeling or sensitivity analyses
   a. Cumulative effects of OWD and other spatial management designations, such as MPAs, that also may exclude fisheries data collections
   b. Test through management strategy evaluation various fisheries management risk policy decisions associated with increased uncertainty due to impacts in fisheries data collections
   c. Conduct research and simulation modeling to better understand the consequence on ecosystem services such as food provisioning if fisheries independent surveys are excluded from OWD areas.
7. Following on findings from ICES Workshop on Unavoidable Survey Effort Reduction 2 Design, test, implement, and report findings on flexible survey designs for new surveys that are resilient to changes caused by long-term or short-term survey disruptions.
8. Establish and share consistent monitoring approaches and standards at the project, regional, and ecosystem levels in order to effectively monitor potential habitat changes due to OWD that have the potential for population level consequences with the following priority foci:
   a. Data should follow Findability, Accessibility, Interoperability, and Reusability (FAIR) guiding principles for scientific management and data stewardship (Wilkinson et al. 2016)
   b. Statistical design
   c. Survey methods
   d. Calibration & Integration of Monitoring Approaches
   e. Linking across spatio-temporal scales (Individual turbines to OWD to Large Marine Ecosystems) and
   f. Modeling approaches, including use of project and regional survey information to account for cumulative impacts on populations, habitats, and ecosystems
9. Within an overarching offshore renewable energy strategy, organizations could leverage their extensive interdisciplinary expertise in marine science and data collections to ensure timely, precise, and accurate information for assessments is maintained.

Conclusion

Sizeable portions of the marine environment will be impacted by OWD in order to address global decarbonization efforts and the objectives of many countries to advance new renewable energy technologies. As such, large-scale OWD will soon occupy large areas of fisheries data collection domains. The disruption of OWD on fisheries independent surveys is also compounded with an increasing marine spatial squeeze from other human activities that can limit the operation and design of existing long-term time series, such as that due to marine protection areas, oil and gas, aquaculture, and future floating OWD. While this may be an important opportunity to address the issues of global climate change, like any other marine energy industrialization required to meet society's energy needs there will be interactions with the marine ecosystem. We are now beginning to understand that the transition to large-scale fixed and floating OWD technologies across our marine ecosystems will result in large-scale disruptions to existing fisheries independent surveys. These data collections are required to be timely, precise, and accurate in order to meet the various societal management objectives that they have been designed to address. Long-term recurring fisheries independent surveys provide robust information necessary for governments to sustainably manage marine resources for food security, conservation, shipping, energy, and other uses. If our ability to conduct fisheries independent surveys is eroded or disrupted, our ability to effectively manage these objectives will become more uncertain with potentially deleterious effects on resources and those dependent on their effective management such as fishing communities, conservation interests, and broader society. Significant effort is now needed to better understand the interactions of our scientific operations with OWD and to design and implement solutions to mitigate the inevitable impacts. While this is a major challenge to our scientific community, it also may represent one of the most significant opportunities to advance new technologies, sampling strategies, and estimation methods, allowing scientists to reimagine our survey and assessment enterprises. The history of other natural resource extractions, including fisheries, shows that it is imperative to fully account for the impact of this development. The effects of postponing study to a later date or externalizing the cost as a problem to solve another day could be severe. Now is the time to scale up these efforts to better understand how we can adapt our fisheries science to the transition to large-scale OWD.

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Author contributions

Conceptualized the paper: AL, YA, FG, AS, FH; Methods and survey development: AL, AS, YA, FG, FH; Conducted the analyses: AL, DB, YA, FH, FG, AS, JL; Figures and tables: SH, DB, FG, TT, AS; All authors contributed to writing, review and editing of the paper.

Supplementary data

Supplementary material is available at *ICES Journal of Marine Science* online.

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Data availability

The data underlying this article are available in the article and in its online supplementary material.

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