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The role of acoustic telemetry to assess the effects of offshore wind infrastructure on fish behaviour, populations and predation

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ABSTRACT

Inshore and offshore coastal regions are becoming increasingly occupied by anthropogenic infrastructure. This trend will continue with the drive for offshore renewable energy development to reduce carbon emissions and provide energy security. The introduction of structures to the marine environment can have direct and indirect effects on benthic and pelagic habitats, and subsequent impacts on species contributing to these ecosystems. Fish are both prey and predators and, therefore, important components to the functioning of food webs in these environments. Should their behaviour, distribution and/or populations be altered by introduced structures then it is important to understand the direction and magnitude of effects, both at local and regional seascape scales, to understand how these effects may influence ecological interactions. The migratory behaviour of some fish species also contributes temporal and spatial variability and uncertainty to observed patterns, which should be characterised to provide a fuller understanding of the consequences of introduced structures. Acoustic telemetry provides insights into the movement and behaviour of individual fish at scales from single wind turbines to regional networks of offshore wind farm developments. Here we review how acoustic telemetry has added to the understanding of fish behaviour around introduced structures and discuss how its use can be (and is being) expanded to provide a wider ecological understanding of the impacts of offshore wind farms through collaborative networks, and integrated research techniques and analyses.

1. Introduction

The expanding use of marine space and seabed for renewable energy generation will see an increase of structures and materials in the water, including wind or tidal turbines, wave energy converters, subsea cabling, moorings and scour protection [1]. Offshore wind is the leading method of marine renewable energy generation with global capacity estimated to have been 48 GW in 2021, and projected to reach 270 GW by 2030 [2,3]. Within the UK EEZ, approximately 2300 km^2 of seabed is assigned to operational wind farms, with over 3000 turbines of varying size and design currently generating electricity or under construction [3,4]. Under a Balanced Growth Net Zero Pathway model produced for the UK government, generating capacity would grow to 95 GW in 2050 (11.3 GW at end of 2021) [3], with associated increase in turbines, infrastructure and seabed area designated to fixed or floating wind farms [5].

The introduction of anthropogenic structures to the marine environment (e.g. oil and gas infrastructure, wind farms, aquaculture systems) can have direct and indirect effects on the host ecosystems [6–10], and their ecological connectivity [11]. Given the large upscaling of the wind energy industry planned for the coming decades, project specific and cumulative effects, at local and regional scales should be assessed in order to understand the positive or negative consequences, potential mitigation or enhancement options, and provide evidence for future development consenting policy and spatial planning [12,13]. The behaviour and distribution of fish in these modified environments will likely be altered [14–19]. However, knowledge of how, and to what extent, these will affect their populations, communities and any marine species that prey upon them is in its infancy and will benefit from the application of contemporary research techniques (e.g. [20–22]). Acoustic tracking of fish has proved invaluable in describing their movement and behaviour [23–25] and has potential to fill important

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knowledge gaps on the impact of anthropogenic activities in aquatic systems [24]. Here we review how this method and associated analyses have, and could be, used to better understand the impact of the large-scale introduction of offshore wind farms on fish ecology, behaviour, and predator prey interactions. The application of acoustic telemetry to assess the effect of a rapidly expanding offshore marine renewable energy industry has not previously been discussed in detail, making this a timely review.

2. Potential effects on fish and their predators

Demersal and pelagic marine fish can be attracted to physical structure, either on the seabed or in the water column, due to the enhancement of favourable habitat and/or protection from predators [26,27]. The aggregating effect around artificial structures found on the seabed has often led them to be termed 'artificial reefs' [28], and when intentionally introduced are mostly used to restore habitat to enhance fish diversity or abundance [29]. The effect can be created unintentionally through accidents, such as shipwrecks [30], or by structures used for other activities, such as oil and gas extraction, aquaculture and marine renewable energy [7,31,32]. Offshore wind farms have the potential to represent the largest introduction of artificial structures into the offshore marine environment, greater than oil and gas industry both in terms of number and spatial extent [1,33]. Moreover, they will provide a network of unintentional artificial reefs or aggregation devices at both local and regional scales that will influence the behaviour, distribution and connectivity of fish populations and their predators (e.g. Fig. 2 (a)) [34–36]. Whether a change in fish abundance around wind farms results from redistribution due to attraction towards the structures or increased in biomass through enhanced reproduction is still to be determined [37]. There is, however, reasonable evidence to suggest both mechanisms occur around artificial structures, including wind turbines, and that structure age and complexity influence how these consequences occur [31,38,39].

Diadromous fish will likely encounter offshore wind farm infrastructure during their migrations but the potential impact on these is less understood than those previously described for other marine fish species. Many diadromous fish are protected under national or international legislation (e.g. EC Habitats Directive protection in Europe for Atlantic salmon *Salmo salar*, Sea lamprey *Lampetra fluviatilis*, Allis shad *Alosa alosa* and Twaite shad *Alosa Fallax*) and thus have high conservation value. Monitoring these species at sea is particularly difficult due to their relative scarcity in the marine environment. Indeed, a key knowledge gap is understanding the connectivity of these populations to offshore wind farms to enable potential impacts to be assessed.

The redistribution and/or concentration of fish into wind farms is expected to modify fish foodscapes for higher predators, including humans (i.e. fisheries). Some of the soft and flat seabed currently preferred for wind farms have been fundamentally altered and degraded by decades of fishing activity (e.g. the North Sea: [40]). Wind farm structures will create complex, hard-substrate habitats that can attract fish and alter abundance and species [41,42], potentially restoring past losses of habitat for both prey and predators. Harbour porpoises (*Phocoena phocoena*) have been found to alter their occurrence and feeding behaviour in response to large offshore structures [43], while some individual harbour seals (*Phoca vitulina*) demonstrate striking grid-like movements patterns focusing on wind turbines and subsea cable infrastructure during putative foraging [44]. These studies provide compelling evidence that wind farms could likely play an important role as foraging areas for several marine mammal species. Gathering direct empirical evidence on how predator-prey interactions can be, and are being, altered by the introduction of wind turbines will inform how wind farms might be developed to limit negative impact and promote positive effects on important fish and marine mammal populations (e.g. [45]; UK government's Marine Net Gain).

3. Acoustic telemetry technology

Tracking the movement of free-ranging animals provides invaluable data on environmental and biological interactions in both space and time [46]. Acoustic telemetry has been particularly useful for gathering such data for marine fish species [22,46–48]. The technique relies on the external attachment or internal placement of acoustic transmitters ('tags') to individual animals, which each emit a unique identification signal (or ping). These may be detected ('heard') and stored by subsurface data-logging hydrophones ('receivers'), which provide presence data at fixed locations, or tracked from receivers on vessels or gliders (Fig. 1). Tag variants also transmit other sensor data from the animal, such as depth and temperature and acceleration, which can enhance 3D spatial positioning [22]. Current battery technology allows tracking of fish for up to 10 years in larger species, with only very small species or juveniles excluded from tagging due to size constraints. However, battery life constraints may be overcome for suitable species with the development of a self-powered acoustic transmitter (SPT) that harnesses the biomechanical energy of the fish's swimming motion, which has the potential for life-long activity [49]. The battery life of long-term receivers can also be measured in years (up to 5) providing potential for long deployment periods. Nevertheless, in many studies, receivers are serviced (e.g. data downloaded and battery checked) more regularly (e.g. twice a year) to reduce the risk of valuable stored data being lost due to equipment loss, damage or malfunction.

Use of the same encoding method in acoustic signal transmission (e.g. pulse position modulation (PPM) or binary phase-shift keying (BPSK)), any tagged fish can, in principle, be detected on any receiver [50]. This compatibility across equipment enables linking of local, regional and international networks of receivers that can each be funded and maintained by different research projects, and/or national agencies. Such collaborative initiatives, including Florida Atlantic Coast Telemetry Network (FACT), Atlantic Cooperative Telemetry (ACT), National Science Foundation's Long Term Ecological Research network (LTER), Australian Integrated Marine Observing System's (IMOS) receiver network, European Tracking Network (ETN) and Ocean Tracking Network (OTN), provide the opportunity for large scale, cross-ecosystem and cross-boundary detections and collaborations, increasing understanding of fish movement and behaviour in migratory and highly mobile species [51–56]. However, within the most dominant method (PPM), protocols can still differ between manufacturers, limiting compatibility to the same purchased equipment, leading to calls, and recent progress, for more open source and/or standardised coding protocols [50].

4. Acoustic receiver arrays and integration

The location of autonomous receivers and/or the design of receiver arrays will determine the movement or behavioural data that can be gathered from tagged animals and, ultimately, the research questions that can be addressed [23].

Large scale (regional, national or continental) movements of individuals have been obtained from receivers and arrays positioned 10s–1000s of kilometres apart, stationed at strategic locations around coastlines or offshore [55,57]. Tagged animals need to pass sufficiently close to receivers to be detected (e.g. <1000m for the highest power tags; but see [58]). The probability of detection increases with the strategic positioning of receivers using prior knowledge of putative movement or migration routes, the array spatial coverage [23] and knowledge of habitat to prevent acoustic shadowing. It is common practice to increase spatial coverage through data sharing among independent receiver arrays, often as part of the collaborative networks previously detailed [53–55]. High density receiver 'curtains' or 'gates' across estuaries and larger water bodies have been successful in increasing the detection probability of tagged animals, and this technique has been especially important for revealing movement and

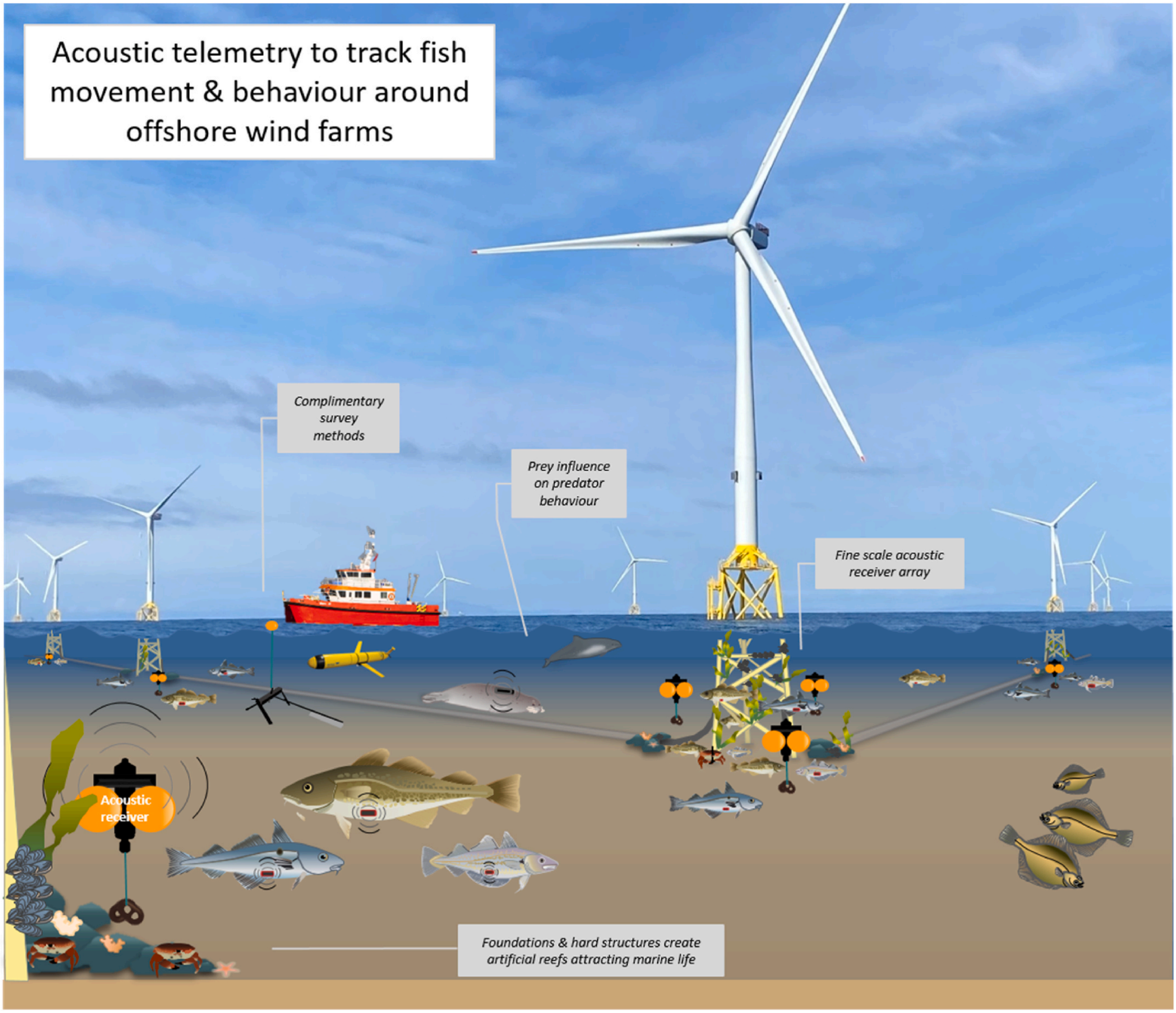


Fig. 1. Schematic of an acoustic telemetry array at an offshore wind farm with complimentary survey methods.

migratory behaviour in anadromous fish species [59–63]. Detections from mobile transceivers attached to marine mammal predators (grey seals *Halichoerus grypus;* Fig. 1) and wave gliders have also been used to augment fixed array detections and to estimate natural mortality in highly mobile Atlantic bluefin tuna *Thunnus thynnus* [57].

Smaller spatial scale receiver arrays have been designed to address species- or site-specific (multi-species) questions related to fish ecology, movement behaviour and management, including species presence, residency, habitat use and population assessments [64–67]. Such arrays now have the potential to explore how networks of structures can influence fish distribution and movements at a wind farm scale [Fig. 1 and **see** Box 1]. Focal studies that near saturate a local area with multiple receivers and use enhanced depth sensor tags can provide accurate 2 and 3 dimensional (3D) positional data to reveal movement dynamics [68]. When networks or clusters of receivers are positioned with overlapping detection ranges, tags can be simultaneously detected on multiple devices, providing fine-scale 3D movement and/or continuous tracking of individuals, useful for revealing social-interactions within fish populations [69], movement patterns around introduced structures [70,71] and to identify fish behavioural states [72].

In addition to meeting research or monitoring objectives, a practical and financial consideration for any acoustic receiver array is how long will it, or can it, be maintained (i.e. data downloaded, receivers cleaned, and batteries changed). The logistics and cost (e.g. vessels, equipment, and person time) quickly escalate with increasing size of an array, and the concomitant tag procurement and catching/tagging of animals. These considerations can limit the scope of some studies, emphasizing the importance of collaborative networks and/or core funding to maintain and potentially adapt arrays for continued monitoring or further research once initial study objectives have been met [23]. Introduction of these techniques into offshore construction sites and operational wind farms result in additional challenges that need considering in the study design, maintenance of arrays and fish capture [see Box 2].

Incorporating complimentary research methods into fish telemetry studies can offer further insight into ecology, behaviour, physiology, and marine community dynamics [48,54,73,74]. Biological samples can be collected from tagged fish for biochemical or genetic analyses. Such data can provide insights into, for example, ontogenetic change in habitat and resource use [75] or patterns in spatial structure and connectivity

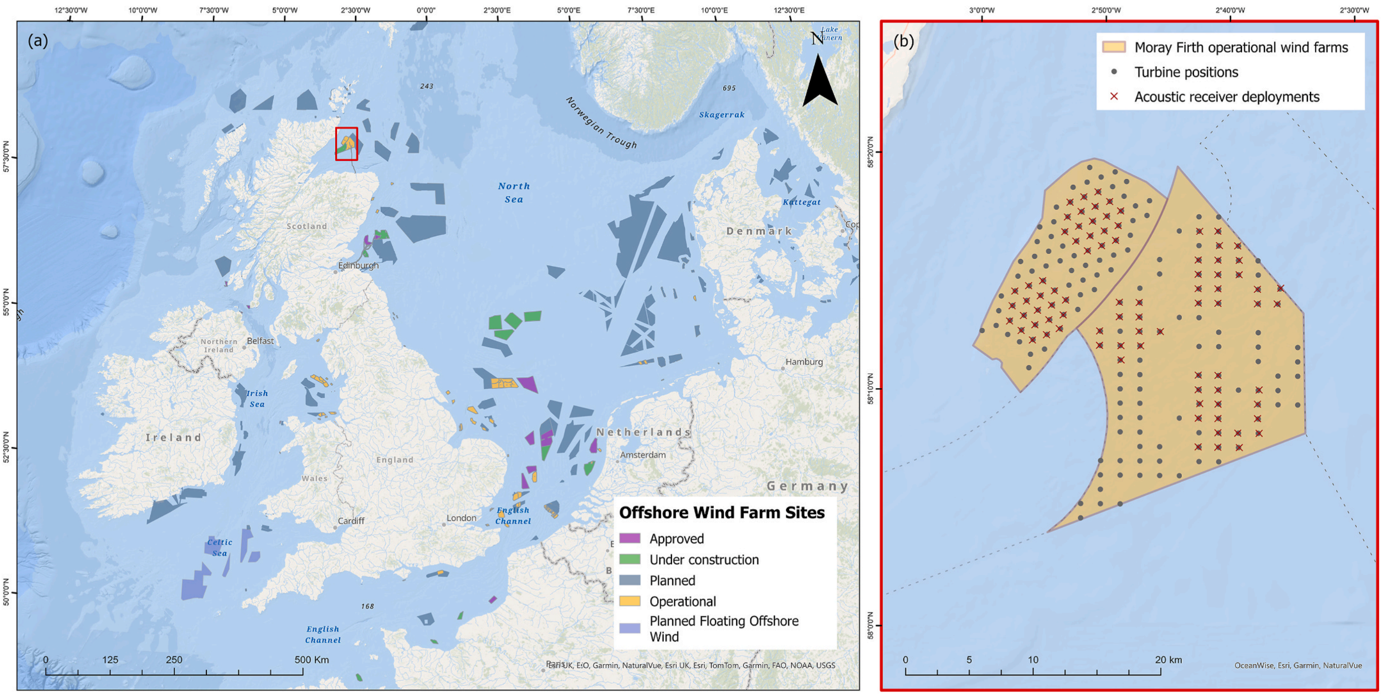


Fig. 2. (a) Current and planned offshore wind farms developments around the North Sea and UK (EMODNet and Crown Estate November 01, 2023). (b) Turbine configuration at two operational wind farms in the Moray Firth, Scotland (Beatrice and Moray East; red box in (a)) and the acoustic telemetry receiver array currently deployed (2021 as part of the PrePARED Offshore Wind Evidence and Change (OWEC) programme project funded by The Crown Estate and Scottish Crown Estate (UK). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

[76], which would not be reflected in telemetry data alone. Co-location or integration of environmental sensors with receivers can offer additional data on abiotic variables, such as temperature, salinity, oxygen or turbidity, which can inform understanding of the drivers of variation in fish presence, activity and behaviour [77–79]. A co-location approach using deployment of echolocation click detectors or broad-band recorders has potential to reveal how predators influence prey behaviour, and vice versa. These approaches could be especially valuable when exploring novel habitat within wind farms that may influence predator prey interactions [43].

5. Contemporary analyses and modelling

The rapid rise in the use of acoustic telemetry and growth in collaborative networks has produced vast quantities of detection and sensor data for a range of fish species and age classes [24]. Combined with access to complimentary data from direct (e.g. biological samples) or indirect (e.g. remote sensed) sources, this has encouraged the application and development of analytical approaches to research questions with wider scope than general fish movement patterns [24,48].

Movement and space utilisation studies commonly use kernel based methods and detection patterns to estimate fish home ranges [80], residency time [70], fidelity [60], connectivity [55], and dispersal measures [62,65], often related to specific sites (e.g. protected areas, offshore structures or rivers) and/or environmental drivers [81]. A standard analysis framework for calculating a range of these measures has been proposed for the multiple species, location and time scales within the large datasets now available [82]. Space use layers derived from modelled telemetry data have also been used in systematic conservation planning within the Marxan decision-support tool, to inform design and efficiency of marine protected areas for important elasmobranch species [83].

A spatial array or "network" of receivers lends itself to the application of network analysis, which uses nodes (receiver locations) interconnected by edges (movement of individuals between receivers) to visualise and statistically analyse presence-absence data [84]. The method examines activity space and identifies core use areas, but also reveals animal movement pathways and shifts in activity areas [84,85], leading to greater understanding of connectivity and dispersal patterns [55,86]. Extending the analysis to include associations of individuals, social structure and aggregation formation have been explored [69,87,88] with further opportunity to apply the method to broad fish conservation themes [89].

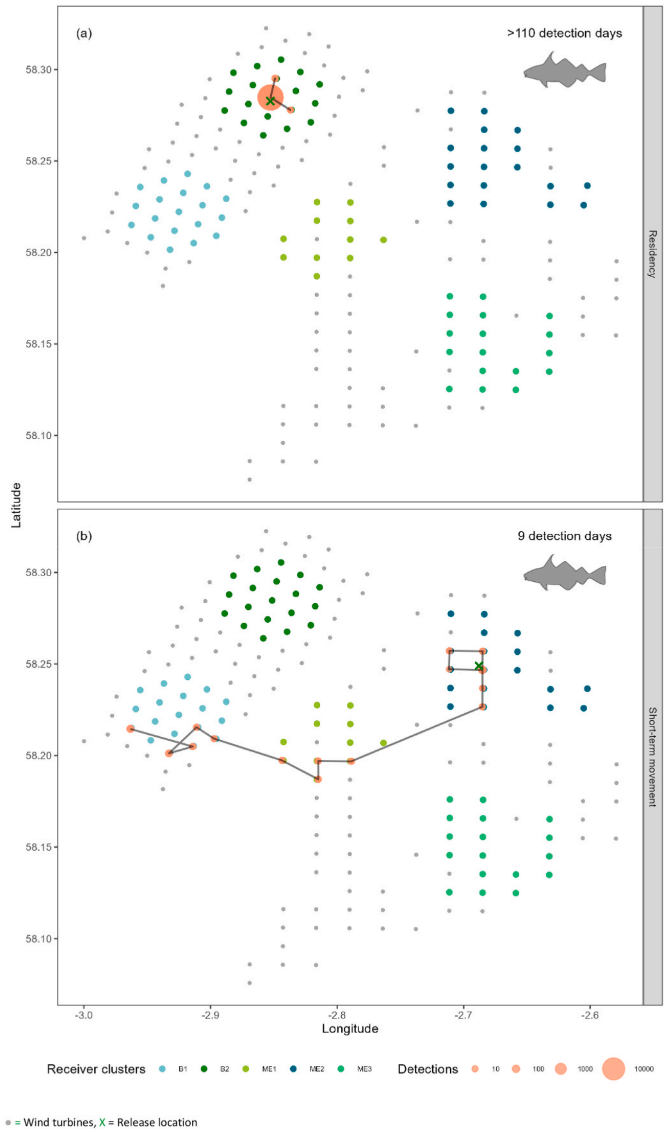
The fine-scale positional data that acoustic arrays can provide for tagged fish have also led to the application of movement models that identify behavioural states using hidden Markov models [90]. These Bayesian models reveal underlying behavioural states, such as resting, feeding and travelling, which are not directly observed (i.e. no continuous monitoring). The occurrence, frequency and/or spatial extent of these states can change with factors such as diel period and fish size, as found in the commercially fished grey triggerfish *Balistes capriscus* [72], important knowledge when attempting to sustainably manage populations.

Fisheries stock models require the estimation of survival, mortality and abundance parameters. These have previously been derived from mark-recapture studies, but sampling can be logistically challenging and result in uncertain estimates in populations where recaptures of individual fish are rare [67]. Acoustic telemetry has been a useful tool in stock modelling studies to compliment or replace these traditional methods. Given this has the advantage of only requiring one capture event, there is higher probability of fish encounters on receiver arrays, and multiple detections over time and space allow construction of detailed encounter histories and improved model parameter estimates [67,91].

Integrating individual based movement and sensor data from telemetry studies into species distribution models (SDMs) has been conceptually considered for fish [92]. Changing from indirect proxies of movement and area-based environmental data collection to direct estimate of movement and environmental variables from sensors on tagged animals has been proposed to enhance the precision of the current

Box 1

Fish behaviour at offshore wind farms: Acoustic receiver detections from two haddock *Melanogrammus aeglefinus* tagged in offshore wind farms in the Moray Firth (Scotland, UK), as part of the Predator and Prey Around Renewable Energy Developments project (PrePARED), demonstrate contrasting patterns (behaviours). Caught and released within 48 h of each other and similar in length (33.5 cm & 31.5 cm), panel (a) presents an individual detected consistently for >100 days at only 3 turbine receivers (primarily 1) since being tagged and released, and (b) shows the movement of an individual between 15 turbine receivers across the two wind farms (3 receiver array clusters) in 9 days.



Haddock (a) detections provide evidence for residency behaviour for 3 months in close proximity to 1 turbine, and haddock (b) illustrates how passage through or movement out of sites can be detected with enough receivers and/or clusters. The latter reiterates the importance of broader scale networks of receiver arrays at planned or built wind farms, e.g. the east coast of UK (see Fig. 1), which could capture larger scale movements and connectivity of fish populations in relation to wind farms.

modelling frameworks. Often used to predict species presence and used to inform spatial management.

6. Telemetry evidence around offshore structures

Few acoustic telemetry studies have specifically investigated the effect of introduced wind farm structures on fish [24,51]. Telemetry studies have, however, been conducted around oil and gas platforms, artificial reefs and fish aggregation devices (FADS), exploring fidelity, residency and movement patterns of fish associated with these structures [70,93–100]. Results from this work provide useful indicators of the types of effect that might be found around offshore wind developments.

An early study in the Norwegian North Sea tagged 29 Atlantic cod *Gadus morhua* ("cod") at a decommissioned oil platform, revealing residency in half of the tagged fish during the three-month study. Further tag detections a year later, and subsequent fishing catches, suggested longer term local residency with some longer distance movements [95]. The impacts of Californian petroleum platforms on local fish populations and communities have been studied over the past 20 years. Latterly this

Box 2
Challenges and opportunities of acoustic telemetry research in and around offshore wind farm sites*:*

Challenges.

- **Mooring receiver arrays in proximity to operational wind farm structures**: *positioning and managing the servicing of receiver arrays to reduce potential loss or damage to equipment, structures or interference with vessels. Including liaising and communication with wind farm developers or operators.*
- **Fish capture and deploy/service acoustic arrays at sites far from coasts:** *the time, effort, equipment, funding and regulatory frameworks required to conduct long-term tracking studies at wind farm sites that are (and will be) between 5 km to >150 km offshore is considerable.*
- **Live capture of benthic fish species in deep waters:** *fish species with closed swim-bladders (physoclisti) can suffer barotrauma after ascent from depths over 30 m, which means they are in sub-optimal condition for tagging. Modification in capture, pre- or post-tagging care and return procedures of fish is necessary to enable survival post release.*

Opportunities.

- **Predation events:** *acoustic tags with temperature and pressure sensors can provide useful fine scale 3D space utilisation of fish, but also the possibility to identify predation (see* Box 3*). Specific 'predation' sensors can also identify these events. These data can be ecologically informative on how the offshore structures act as prey aggregation devices for higher trophic level marine mammals or seabirds, with potential outcomes for fish population dynamics.*
- **Collaboration and wider networks:** *in isolation, an acoustic tracking study can provide detailed information on one or more fish species movement and behaviour. These data are important in understanding ecological interactions with predators and prey within the focal area, which can foster collaboration with other researchers and organisations studying these trophic levels providing a more holistic interpretation. The creation of a wider network of receiver arrays at wind farms across a region or sea, can open the scope of such studies and collaborations to address more broad scale movement and behavioural processes.*

has involved telemetry studies of 17 groundfish (bottom dwelling) species. High intra- and interspecific variability in fidelity to the platforms was found over a 1.5 year period, with evidence of movement between platforms and natural reef habitats [96]. A translocation study, where rockfish (*Sebastes* spp.) and lingcod *Ophiodon elongatus* were caught at platforms and released at natural reefs 19 km away, revealed return (homing) behaviour in a third of the fish, suggesting that a portion had a preference for the artificial habitat [93]. The latest of these Californian studies focused on nearshore reef species caught at a shallow (~50 m) and deep (>200 m) water platform. The four species (cabezon *Scorpaenichthys marmoratus*, grass rockfish *Sebastes rastrelliger*, kelp rockfish *Sebastes atrovirens*, California sheephead *Semicossyphus pulcher*) revealed a high degree of long-term site fidelity (up to 578d), with seasonal patterns in depth (habitat) use [97]. The latter being important when considering decommissioning options and policy that could mean part, or all (i.e. toppled), of the platform is left in place and continues to occupy different depths at the end of their production life [101].

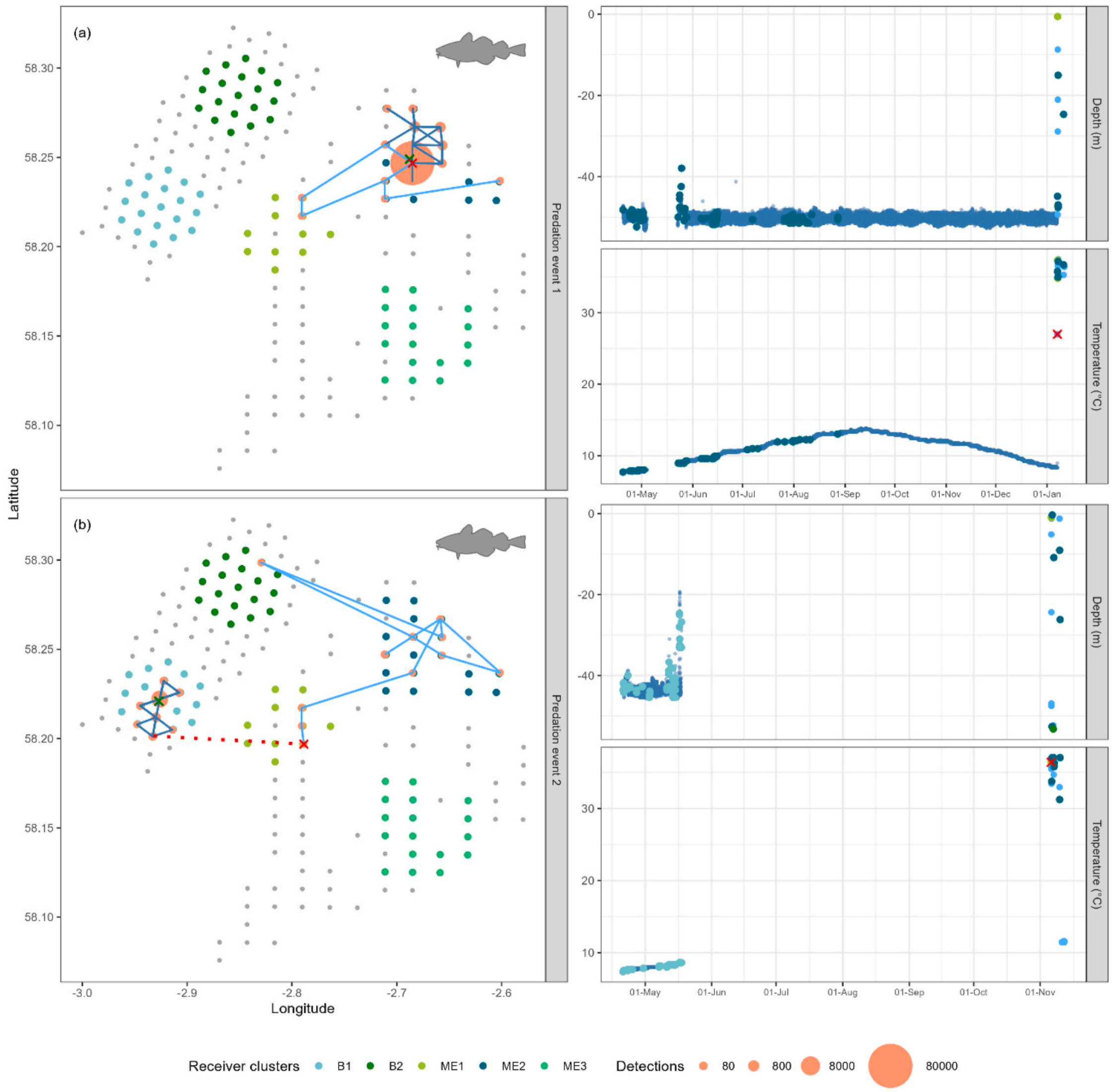
Research at oil and gas platforms and artificial reefs in the Gulf of Mexico ("GOM") have also used telemetry to understand fish behaviour around these structures. In parts of the GOM, platforms provide habitat that supports a large portion of the reef associated red snapper *Lutjanus campechanus* population (e.g. ~70–80 % of age 2 fish in 1992) [102]. Using fine-scale positional data (accurate within ±2–7 m) red snapper revealed affinity to the platforms with >90 % of positions recorded within 95 m of the structures. Home ranges of tagged fish changed with environmental variables and seasons. Short periods of emigration out of the range of receivers were detected, but most individuals returned within 3 days [70]. The blue runner (*Caranx crysos*), a pelagic and schooling species, also remained close to a large platform structure complex for periods of least 7 days [94]. High site fidelity (up to 88 % yr^{-1}) and residency (up to 23 months) of red snapper to introduced structures was equally demonstrated around the extensive network of seabed artificial reefs in the GOM [98,100,103–107]. An analysis of 3D positional data revealed the species used the entire water column around and above seabed structure during spring and summer, suggesting it is not a strictly benthic species in these environments [103].

Using telemetry to study the behaviour and movement of fish around FADs has mainly focused on the large commercially or recreationally important fish species, which FADs are designed to aggregate. Tunas (*Thunnas* spp. *& Katsuwonus* spp.*)* and dolphinfish (*Coryphaena hippurus*) have been particularly well studied [99,108–114], demonstrating a high degree of association, residency and homing behaviour around floating devices. These results have provided insight into the attraction and behaviour that might be expected around floating wind turbine structures as these developments increase, and how they might affect local recreational and commercial fisheries [115].

Before 2024, studies directly researching the effect of offshore wind farm infrastructure had only been published for sites in European waters (Fig. 3), where large development projects have taken place in the past 15–20 years (https://map.4coffshore.com/offshorewind/). Cod at a wind farm in the Belgian North Sea demonstrated high relative levels of seasonal residency (n = 22) at the hard substrate habitat around turbines during summer and autumn [16,116], with crepuscular movements related to feeding activity [117]. Similar turbine residency behaviour of cod was reported at a Dutch wind farm, although there was greater individual and seasonal variation in tagged fish behaviour, with a variety of diurnal patterns emerging [118]. Sole (*Solea vulgaris*) fitted with acoustic tags at the same wind farm revealed little affinity to turbines, or the site itself, with movements at a spatial scale larger than the wind farm being inferred from the lack of detections on the network of receivers, but also substantiated by mark-recapture tagging from fishing trawlers [118]. A recent study, however, found another flatfish species, the European plaice (*Pleuronectes platessa)*, demonstrated residency behaviour during the feeding season between and close to turbines with scour protection at a Belgium wind farm [n = 26, 70 % detected in study area >75 % of days at large: 114]. The study also revealed fine scale diurnal movement between turbine scour protection during the day (main detection peak <25m from turbine) and sandy habitat further away at night (smaller detection peak at ~90m from turbines) [119]. These contrasting behaviours highlight the intra-specific differences in how offshore wind farm structures may alter fish populations and distribution. A previous study at the same Belgian wind farm used triangulated positional data of cod to assess the effects of pile driving sound during construction of a neighbouring turbine array. Modest, yet statistically significant, effects were found during and after the piling, with cod moving closer to the scour protection surrounding the closest

Box 3

Detecting predation events. Offshore wind farm structures have the potential to attract and aggregate fish, therefore become novel foraging areas for marine animals that predate on them. The consequence of these interactions for either prey or predator populations at a local or wider scale is not fully appreciated at present, but with additional evidence of such events the potential population and ecological effects may be assessed and ultimately predicted.



● = Wind turbines, X = Release location, X = First detection after consumption by mammal
Dark blue line = fish movement & detections, Light blue line = mammal movement & detections
Depth and temperature time series graphs present fish (Dark blue) and mammal (Light blue) detections as small dots. A change in detecting receiver (movement) is shown as larger dots with associated cluster colour.

Acoustic telemetry tags with temperature and depth sensors can provide evidence of predation events, which if involving a marine mammal is primarily indicated by the increase in tag temperature to between 35–38°C (mammal body temperature range). When associated with a fish (externally or internally) the tag temperature will reflect the surrounding water, therefore vary with the time of year, so the increase when consumed by a mammal predator is quite stark in temperate waters. These patterns can be seen in (a) panels where detections from a tagged Atlantic cod in the Moray Firth wind farms are shown spatially and as temperature and depth time series plots for 7 months. The fish shows residency behaviour in the ME1 acoustic cluster (particular proximity to 1 turbine) from May to June where the depth is within a relatively small range (–38 to –53 m) and the temperature values reflects the seasonal change in water temperature. The dramatic increase in temperature and depth variation in January, coincides with an increase in spatial movement as the tag is detected on multiple receivers over a short period, indicative of predation by a mammal (i.e. seal or cetacean).The patterns shown in (b) panels illustrates a less resident cod that moves between turbines in the B1 cluster for a 3 week period, but then the tag is not detected on a receiver until 6 months later when its shows the increased spatial movement, high temperature and variability in depth that is indicative of a marine mammal. The predation event is assumed to have taken place somewhere outside the range of the acoustic array, but the predator has entered the wind farm and been detected after consuming the cod (timing would be dependent on gut residency time) and is moving between the turbines potentially looking for further prey.

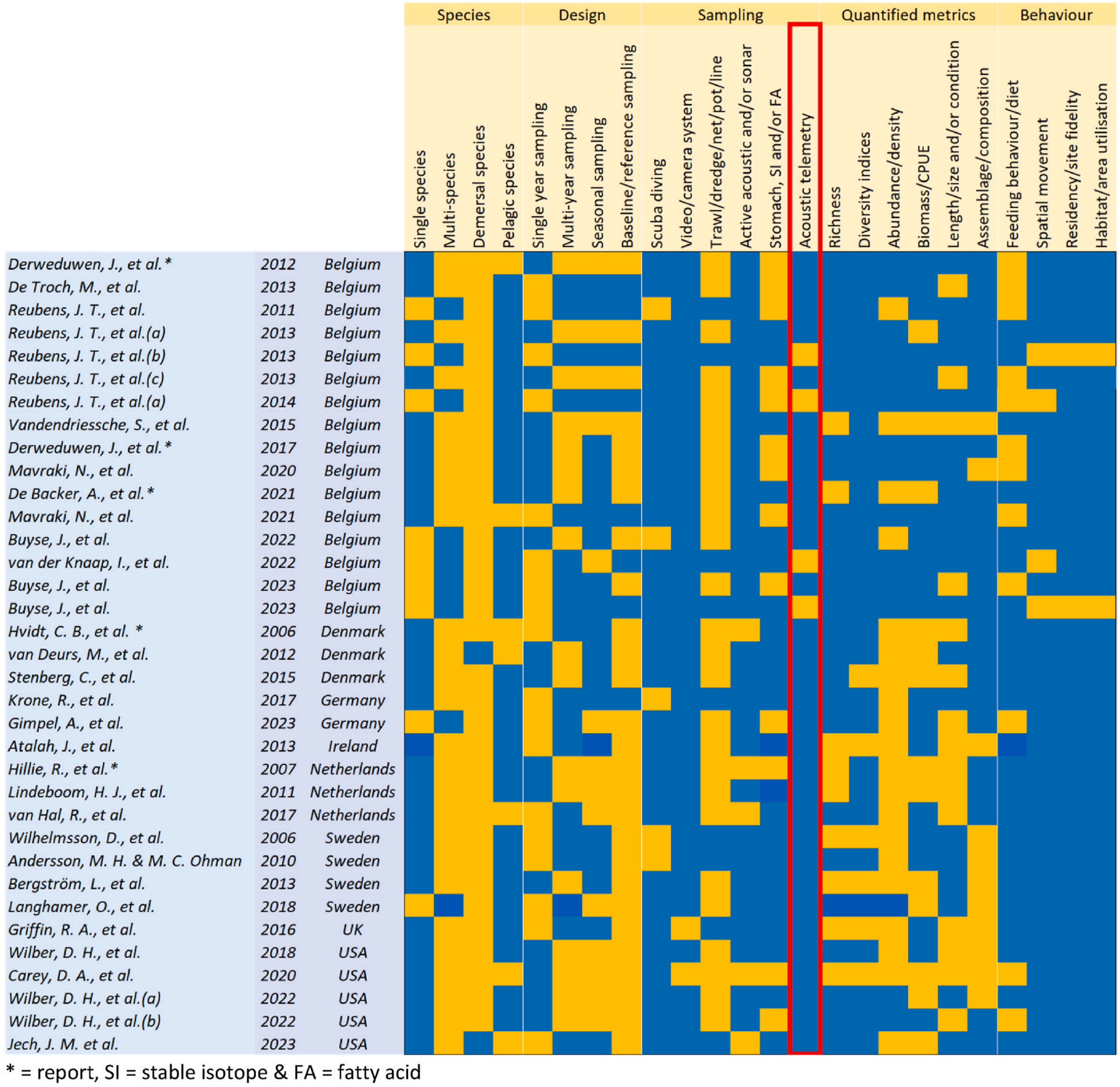


Fig. 3. Peer-reviewed literature and reports (see References and [121]) of studies directly assessing the effect of offshore wind farms on teleost fish (not larval stage) before 2024. Yellow = included in study & & blue = not included in study. Red box highlights studies that used acoustic telemetry to track fish. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
* = report, SI = stable isotope & FA = fatty acid.

turbine and moving further away from the sound source, but all tagged fish remaining within the estimated exposure area [120].

Complementing the studies on fish behaviour, a recent telemetry study has revealed turbine scour protection is also useful habitat for a commercially important marine invertebrate, the European lobster (*Haomarus gammarus*). Thirty three tagged individuals demonstrated high levels of residency at turbine tagging sites (70 % of time) with 50 % of detections recorded within 35 m of the hard substrate protection [122]. Further illustrating the application of acoustic telemetry to detail the impact of OWF infrastructure on behaviour and movement of important marine animals, beyond the fish community.

7. Discussion of future telemetry research around offshore wind farms

Fish telemetry studies around offshore structures support the body of evidence indicating these sites alter fish movement and behaviour and act as important habitat for attracting (aggregation or production) a variety of fish species.

With global offshore wind generating capacity predicted to grow annually until 2030, the number of wind farm installations could potentially triple in the coming decade [2]. This expansion will necessitate the installation of thousands of wind turbine structures of varying design and complexity, fixed foundations on the seabed or as floating devices, with the accompanying moorings, subsea cables, dynamic and floating cables, substation platforms and scour protection. The need to expand into deeper water will become pressing, as available space in shallower waters becomes limited. The construction will be one of the largest introductions of artificial structures into the global offshore marine environment in terms of number and spatial extent, and will produce novel subsea and sea surface seascapes [1,33]. Large areas of uniform, regularly spaced habitat are rare (if not unique) in the natural marine environment, rather heterogeneous or patchy distribution of habitats (and organisms) is the norm [123,124]. OWF sites provide such regular habitat at the local level (Fig. 3 (b)), and with the planned expansion, will create a patchwork of these sites separated by regions of natural (to varying degree) seascape (Fig. 3 (a)). A hierarchical (scale dependent) mosaic of regular (local site) and irregular (regional sites) habitat patches, will elicit different responses by fish depending on the scale and species life history characteristics [125]. How these responses will shape fish movement, population dynamics and community structure, are key and unknown ecological impacts of OWF construction. In later phases of the industry's development, early projects will be coming to the end of their planned life, requiring careful management of de-commissioning or re-purposing of structures across these networks of sites [126,127].

Acoustic telemetry could help fill knowledge gaps by revealing details of individual fish behaviour at both fine (<10 m) and broad (>1000 km) scale. The direct effect of pile driving noise during construction of wind turbine foundations has been studied in relation to marine mammals [128,129], but little is known how these events might impact fish [130]. Acoustically tracking the movement and behaviour of individual fish over the period of these events (pre, during and post), in conjunction with other techniques (e.g. passive acoustics, cameras, sonar), could provide detailed data on how fish respond to impulsive noise sources and whether effects may be cumulative and/or persistent [130]. For reef or hard substrate associated species, the habitat provided by regular turbines and multiple wind farm sites may promote a metapopulation environment over local and regional spatial scales. In this instance, residency, dispersal patterns (immigration/emigration) and distances, and survival rates available from telemetry studies would be combined with species population estimates (abundance, biomass or density metrics) from complimentary surveys at wind farms (Fig. 1), e.g. underwater cameras [20,131] or fisheries hydroacoustic and trawl surveys, to assess changes in population structuring. Species that migrate and move over much larger distances, such as salmon and tuna, may not be so intimately linked with the introduced habitat but must still navigate the new seascape created by OWFs. Notably, these sites may become areas of increased foraging ('hotspots') for some species, shelter from predators for others, or even barriers during spawning migration. Maintaining a network of telemetry arrays (including wind farm sites) that share detection data could help detail changes in movement patterns with increasing regional development (e.g. Interreg FISH INTEL project: FISH INTEL Interreg France (Channel) England - University of Plymouth).

These approaches also provide opportunities for exploring ecological interactions around OWF. A growing number of studies have demonstrated that marine top predators such as marine mammals may be attracted to structures such as OWF [43,44,132]. Observed seasonal or diel patterns of occurrence and foraging around structures seem likely to be related to the behaviour of different prey species [133,134]. However, limited information on the behaviour of individual fish around artificial structures constrains current understanding of how any changes in prey distribution around OWF might shape predatory behaviour and influence top-down ecological interactions. Networks of OWF could aggregate prey, for example, potentially providing predictable foraging patches for predators such as seals (see [44]). In turn, this may shape predator-prey interactions to the extent that they constrain recovery of some depleted species such as cod [135,136]. Acoustic tracking of individual fish around networks of OWF provides one of the most promising avenues for understanding these interactions in more detail. Broader scale data on residency patterns or movements of individual fish across networks of OWF may inform understanding of drivers of seasonality in marine mammal or seabird activity. At a finer-scale, acoustic tags with pressure sensors could, for example, be used to explore whether observed diel patterns in porpoise foraging around structures [43,134] are in response to either fine-scale horizontal or vertical movements of prey at night. Where larger marine mammal predators are known to concentrate their foraging in areas containing acoustically tagged fish, animal-borne (e.g. seal) acoustic receivers can provide direct information on predator-prey encounters [137–139]. However, such studies would be extremely challenging around offshore wind farms given the difficulty of capturing and instrumenting individual predators that are likely to forage in specific offshore sites. On the other hand, additional sensors within acoustic tags placed on fish caught in these offshore areas can still provide information on predation events [22,140,141]. For example, marine mammal predation attempts may be detected through sudden rises in tag temperature, or depth profiles (see Box 3). Similarly, predation by other fish can be detected using predation tags which change their identification code after contact with stomach acid [141]. These evolving technologies [140] and analytical approaches for detecting predation events [142] are increasing opportunities to understand both the prey base and predator-prey interactions around offshore structures. Combining complimentary survey and analytical techniques, including acoustic telemetry, underwater cameras and energetic models, should now help reduce knowledge gaps and improve evidence-based decision making regarding the ecological impacts of upscaling OWF.

Acoustic telemetry has been used to assess fish behaviour, movement and interactions over relatively short time frames (<10 years), but findings also need to be considered within the context of climate change that is continuing to alter the temperature and chemistry of the oceans over much longer periods, including intermittent severe marine heatwave events [143]. Increasing water temperature and reduction in dissolved oxygen are known to alter marine fish community structure, diversity and distribution over decades [144–146], with predicted effects on predators [147,148]. The presence, condition and behaviour of fish utilising current or future OWF sites will have been moulded by the climate driven changes in biotic (prey and predators) and abiotic (temperature, salinity, oxygen) factors. It will require a longer term (>10 year) and larger scale (international) vision of acoustic telemetry receiver networks (i.e. ETN and OTN) and tagging programs to enable the method to assess how large scale OWF development (fixed and floating foundations) and ongoing climate induced ocean changes might interact to shape fish behaviour and movement in a shifting seascape.

CRediT authorship contribution statement

Anthony W.J. Bicknell: Conceptualization, Funding acquisition, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Samuel Gierhart:** Investigation, Data curation. **Matthew Newton:** Writing – review & editing. **Robert Main:** Investigation, Data curation, Writing – review & editing. **Paul Thompson:** Funding acquisition, Writing – review & editing. **Matthew J. Witt:** Conceptualization, Funding acquisition, Writing – review & editing.

Ethics statement

Fish tagging activities were reviewed and signed off by University of Exeter Animal Welfare and Ethical Review Body. Tagging of fish was conducted under UK Home Office project licences held by Scottish Marine Directorate and University of Exeter, and personal individual licences held by project team members. These licence permits, and procedures within, are regulated under the UK Animals (Scientific procedures) Act 1986.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anthony Bicknell reports financial support was provided by The Crown Estate. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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