ICES Journal of Marine Science, 2024, Vol. 0, Issue 0, 1–12
https://doi.org/10.1093/icesjms/fsae083
Received: 30 June 2023; **revised:** 24 May 2024; **accepted:** 30 May 2024
Original Article

ICES CIEM
International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

Structure size may affect fish density around oil platforms

Joshua M. Lawrence[1,*], **Michael R. Heath**[2], **Douglas C. Speirs**[2], **Paul G. Fernandes**[1]

[1]The Lyell Centre, Heriot-Watt University, Research Avenue South, Edinburgh EH14 4AP, United Kingdom
[2]Department of Mathematics and Statistics, University of Strathclyde, Livingstone Tower, 26 Richmond Street, Glasgow G1 1XH, United Kingdom

*Corresponding author. The Lyell Centre, Heriot-Watt University, Research Avenue South, Edinburgh, EH14 4AP, United Kingdom. E-mail: Joshua.lawrence@hw.ac.uk

Abstract

Thousands of offshore oil and gas platforms have been installed worldwide and are known to act as artificial reefs. Many platforms are nearing the end of their operational lives and will soon require decommissioning, but uncertainty remains about the impacts of these structures, and their removal, on the environment. Fish aggregate at platforms, but little is known about the extent of these effects in the North Sea and the causes of variability in these associations. Here, an uncrewed surface vessel (USV) was used to collect fisheries acoustic data on distributions of schooling and non-schooling fish around six oil platforms, collecting data within tens of metres of four of the surveyed platforms. In areas with more platforms, more non-schooling fish were found, and the probability of detecting fish schools was higher. Interplatform variability was found in trends in non-schooling fish density with increasing distance from platform, but the relationship was found to be strongest and most negative at the larger platforms. These findings may influence future management decisions around the decommissioning of these platforms, particularly if some structure is to be left in place to maximize the potential benefits associated with these artificial reef effects.

Keywords: uncrewed surface vessel; fish; fisheries acoustics; man-made marine structures; decommissioning; oil platform

Introduction

Offshore oil and gas platforms, installed throughout the world's oceans since the mid-20th century, act as artificial reefs (Baine 2001). Now, numbering in their thousands worldwide, they increase local productivity and biodiversity, supporting a diverse range of taxa (van Elden et al. 2019). Indeed, in the waters off the coast of California, oil platforms have been recorded as exhibiting the highest secondary production of fish, per unit area of seafloor, of any marine habitat for which such measurements exist (Claisse et al. 2014).

Many aspects of the biological communities associating with offshore platforms have been studied, including the epibenthic and fouling communities (Whomersley and Picken 2003, Schutter et al. 2019, Love et al. 2019c), fish (Love and York 2005, Fujii and Jamieson 2016, Love et al. 2019a) and invertebrate assemblages (Page et al. 2006, 2019, Todd et al. 2018, Love et al. 2019c), and top predator behaviour and distributions (Todd et al. 2016, Clausen et al. 2021, Fernandez-Betelu et al. 2022). However, there are still questions about the environmental impact of these structures, and about their overall ecological value. Answers to these questions are needed, because managers in many areas are now being faced with decisions regarding the fate of these structures as they reach the end of their operational lives.

In some areas, rigs-to-reefs programmes exist, where platforms are either left in place or toppled in order to maintain the biological communities supported by platforms following their decommissioning (Kaiser and Pulsipher 2005). However, in some other areas, no such programmes exist, and the local legislation either requires case-by-case assessment of decommissioning options, or requires full removal by default (with occasional derogations possible in exceptional circumstances) (Jørgensen 2012). In these cases, it is important to understand the specific ecological impacts of the platform in question so that well informed management decisions can be made. These ecological impacts can depend on a wide range of environmental variables, including location (at both large and fine scale), water depth, and hydrodynamic regime, and structure-characteristic variables, including size, design, and construction material. Understanding how these variables relate to, or indeed define, the biological communities associating with specific platforms, and particularly if consistent are relationships identified at a regional scale, can facilitate effective and efficient decision making (Fowler et al. 2020).

Many studies of the communities around oil platforms have been focussed on a single platform, and so are not able to resolve the causes of interplatform variability (Løkkeberg et al. 2002, Soldal et al. 2002, Fujii and Jamieson 2016), or have compared communities between platforms without attempting to use platform characteristics to explain any observed differences (Love et al. 2000, Claisse et al. 2014). The variations in fish densities between different parts of oil platform jackets (interior and exterior crossbeam, jacket legs) have been studied (Meyer-Gutbrod et al. 2019), as has the influence of differing structural complexity of different platform designs (Love et al. 2019a, 2019b). Some work has investigated changes in the ecological communities associated with platforms as they age (as a form of succession, from colonization to climax community) (Todd et al. 2018, 2020, Torquato et al. 2021), but little effort has been made to investigate platform characteristics (e.g. size) as a driver of interplatform differences (Lawrence et al. 2024) in the ecological relationships observed. Platform depth, which necessarily correlates with size/weight for surface-piercing structures installed on the seabed and so could be considered as a proxy for platform size has been examined (Stanley and Wilson 1998), and platform surface area has been reported but not related to observed variability (Claisse et al. 2014). One explicit use of platform weight data as a metric of interest assigned arbitrary buffers of different sizes to platforms of different weight ranges as part of areal habitat classification (Wright et al. 2020). This was based on the presumption that large platforms will have larger influence, but did not provide evidence to support the idea.

That larger platforms will have a larger influence on the environment than smaller platforms is, however, a reasonable hypothesis. Any potential mechanism by which a platform influences or provides opportunity for a biological community scales with size (for a consistent platform type or design (Lawrence and Fernandes 2022)). Such mechanisms include providing a hard substrate on which sessile organisms can settle (Stachowitsch et al. 2002, Love et al. 2019c), providing complex 3D structures which act as potential refugia or resting places for fish or invertebrates (Rogers et al. 2014, Komyakova et al. 2019, Price et al. 2019), and affecting local hydrodynamics, creating a wake or increasing vertical mixing downstream potentially affecting local productivity and fish behaviour (Floeter et al. 2017, Schultze et al. 2020, Daewel et al. 2022).

One reason many studies have focussed on only a single platform is that collecting ecological data around operational oil and gas platforms presents numerous logistical challenges. In the North Sea, 500 m safety zones are in place around all oil and gas platforms, entry to which is only granted through a permitting process, controlled by the platform operator, which requires certain high-level safety specifications for large vessels. One solution to these complications and risks, is the use of a small vessel which poses no threat to platform infrastructure. Uncrewed Surface Vessels (USVs), capable of over-the-horizon control via satellite link, provide a survey platform to which a range of sensors can be mounted, while offering a low-risk (and low-carbon) alternative to traditional survey vessels (Patterson et al. 2022).

Here, fisheries acoustics sensors were deployed from a USV to collect data of fish distributions within and around the 500 m safety zone of four North Sea oil platforms. Fisheries acoustics provides a means by which fish densities can be measured rapidly, over large areas, at very high resolution (Simmonds and MacLennan 2005), and so their use, in combination with USV technology, present an effective way to investigate fish distributions and density trends in the waters around multiple oil platforms in a cost- and time-efficient manner.

This work aimed to characterize the distributions of fish around oil platforms, and to examine the potential influence of platform size on the identified relationships between fish density and distance from platform. We investigated the null hypotheses: (i) that there is no detectable relationship between fish density and distance from platform, and (ii) that platform size has no influence on the relationship between fish density and distance from platform.

Methods

Acoustic data were collected using a Simrad EK80 scientific echosounder deployed from a USV from 19th–24th August 2021, in the waters off northeast Scotland. The echosounder consisted of an EK80 WBT (wideband transceiver) Mini powering a dual frequency transducer, emitting frequency modulated pulses at 38 and 200 kHz simultaneously, at a 1-Hz ping rate and at 500 and 100 W, respectively. The system was calibrated using standard protocols (Demer et al. 2015), prior to the survey on 18th August 2021. The USV measured 4.3 × 2.2 m, weighed 750 kg, and was capable of non-autonomous (i.e. human-controlled via satellite link) over-the-horizon operations, and so was permitted to enter the safety zones around four oil platforms due to its small size. The survey was designed to collect data over a gradient of distances from each platform in as many approximately orthogonal directions as possible, so a cruciform design was used, centred slightly offset from the platform location. At some platforms, the arrival or departure directions at/from the platform were used as one or more arms of the cruciform pattern; where these were not of the same compass bearing, the corresponding arms of the cruciform bisected the angles between the arrival/departure legs, rather than being precisely orthogonal to either angle. Due to time constraints on the survey duration, it was not possible to include all four arms of a cruciform design at all platforms. The survey track also passed by the edge of the 500 m zone around two further oil platforms as a ‘fly-by’ transect; no additional arms were added to replicate the cruciform pattern. The surveyed platforms have been anonymized, but will be referred to as platforms A–F, in ascending order of substructure weight (weights of 730, 1500, 5200, 11000, 12000, and 34000 t). Where sites involve two or more bridge-linked platforms (near-by platforms, connected via a footbridge), their substructure weights have been summed to a single value, on the assumption that their size-related effects on the local environment will be cumulative. Summary details of each platform and survey is given in Supplementary Table S1.

Acoustic data were processed in Echoview (Echoview Software Pty Ltd 2021), following standard pre-processing and data cleaning (removing noise, bad data regions, the near-field (10 m), and correcting the detected seabed line). Two data processing algorithms were used; the first to isolate and quantify backscatter from schools of swimbladdered fish, and the second to enumerate echoes from individual (non-schooling) fish.

While scattering layers and zooplankton were also present in the acoustic data, these were excluded in this analysis due to the potential non-proportionality and non-linearity between backscatter and organism density or biomass. Due to the lack of alternative evidence gathered during the survey (e.g. plankton net tows), and the available acoustic frequencies, little confidence is possible about the constituent organisms of these scattering layers, and so trends in relative acoustic density, if found, would be uninterpretable.

Fish school isolation algorithm

To identify regions of backscatter from schools of swimbladdered fish, an adapted version of the algorithm presented in Fernandes (2009) was used. This algorithm exploits the strong and consistent scattering from swimbladdered fish across the frequencies used, but was adapted for use with just two frequencies. Pulse compressed volume backscattering strength (S_v; dB re. 1 m^{-1}) data, with a 20logR time-varied gain (TVG) function applied by Echoview, were summed across the two frequencies used, median filtered (to remove isolated scatterers), dilation filtered (to include the edges of schools), and thresholded to −113 dB, cf. the −226 dB used for four frequencies by Fernandes (2009). School detection was run on the thresholded virtual echogram and any schools with a mean $S_v < -55$ dB, or where the backscatter at 200 kHz was 10 dB or more stronger than at 38 kHz (to avoid the inclusion of dense zooplankton aggregations) were discarded. Additionally, any schools where the backscatter intensity in the water immediately surrounding the school was within 8 dB of the backscatter within the school itself were discarded; this insured that the strong scattering layers present in the area (Mair et al. 2005) were not included. The final fish school echogram was integrated over 50 m segments of data (elementary distance sampling units, EDSUs), to give nautical area backscattering coefficients (NASCs) (m^2 nmi^{-2}).

Non-schooling fish detection

Echoview's single echo detection (SED) functionality was used to detect echoes from non-schooling fish from the pulse compressed target strength (TS) echograms (with a 40logR TVG function applied by Echoview). This process relies on the recognition of the characteristic form of the transmitted pulse in the echo received by the echosounder, as is only the case when an isolated scatterer reflects the transmitted pulse. In aggregations of multiple targets, echoes overlap causing constructive and destructive interference to distort the pulse shape so that it no longer resembles the transmitted pulse. However, this process is not infallible, and so protocols have been developed to identify areas of low density scattering where single targets can reliably be identified (Sawada et al. 1993). A 25 × 5 m (horizontal × vertical) grid was used to discretize the data, and Sawada et al.'s (1993) indices were calculated, with only areas with values of $M < 0.7$ and $N_v < 0.1$ being deemed sufficiently low density for reliable single target detection. The detected single targets were thresholded to exclude any targets smaller than the expected minimum size of the species of interest. These were cod *Gadus morhua*, haddock *Melanogrammus aeglefinus*, saithe *Pollachius virens*, and whiting *Merlangius merlangus* and threshold TS of −55 dB was used (equivalent to a 4.2-cm gadoid, based on the standard TS-length equation $TS = 20\log_{10}L - 67.5$ (Simmonds and MacLennan 2005)). Retained targets were exported as counts of targets in 50 m EDSUs.

The seabed depth was exported for every ping in the single target echogram, so that the volume of water sampled could be calculated, and the numbers of targets per EDSU could be converted into areal densities of fish.

To calculate the total volume of water sampled in each EDSU (which changed with seabed topography and number of pings in the EDSU), the volume of water sampled in each ping was calculated. For this, the height of the cone equivalent to the volume of water sampled (from 10 m depth to the seabed depth, D_{ping}) (H_{equ}; m) was calculated as

$$H_{equ} = \sqrt[3]{{D_{ping}}^3 - 12^3} \tag{1}$$

and the volume of each ping (V_{ping}; m^3) was then calculated as

$$V_{ping} = \left(\frac{\pi}{3}\right)\left(\tan\frac{\alpha}{2}\right)\left(\tan\frac{\beta}{2}\right)\left(\sqrt[3]{H_{equ}}\right), \tag{2}$$

where α and β are the major- and minor-axis beam angles, respectively.

With the volume of each ping known, the pings assigned to EDSUs based on their timestamp, and the number of SEDs in each EDSU known, areal fish density (m^{-2}) in each EDSU could be calculated as:

$$Dens_{EDSU} = \frac{SEDs_{EDSU}}{n_{EDSU}}\left(\sum_{i=1}^{n_{EDSU}}\frac{H_{equ_i}}{V_{ping_i}}\right), \tag{3}$$

where $SEDs_{EDSU}$ is the total number of SEDs recorded in the EDSU and n_{EDSU} is the number of pings in the EDSU.

Hydrodynamic data

In order to investigate the hypothesis that associations between fish and oil platforms are caused by the platform affecting local hydrodynamics, steps were taken to determine when data in an EDSU were collected 'downstream' of the nearest platform. Outputs from a hydrodynamic model of the North Sea [the Scottish Shelf Model (Barton et al. 2022)] were interrogated to extract a current velocity and bearing for each EDSU. However, the model run period did not cover the survey period (model run from 1993 to 2019, survey period 2021). Instead, a similar period of the tidal cycle was identified, and the time offset required to match EDSUs to the equivalent point in the model data was calculated. This was used to extract surface current data (in u and v, northing and easting, which was then converted to velocity and bearing) and if the current direction was within ± 22.5° of the bearing from the platform to the mid-point of the EDSU, the EDSU was deemed to be 'downstream' of the platform.

Modelling

Generalized additive models, built in R (R Core Team 2020) using package *mgcv* (Wood 2017), were used to investigate the relationships between fish density and distance from platform. Models built for non-schooling fish areal density using a gaussian error distribution and log-link function (selected due to the log-normal distribution of the data) generated skewed residuals (Supplementary Fig. S1). A log-transformation was therefore applied to the density data, which, along with an identity link function, resolved the non-normality of the residuals (Supplementary Fig. S2). The fish school data were modelled only as presence/absence using a binomial error distribution; due to the extreme variability and skew of the fish school NASC data.

The distance from the nearest of the 6 platforms surveyed was calculated for the mid-point of each EDSU, and models were built with data 10 km or less from the surveyed platforms, using a three-way interaction term between distance from platform, a platform identity as a factor variable, and 'downstream' vs 'not downstream', so that a different relationship was fitted for the downstream and not-downstream data at each platform. Due to fish behavioural changes with the diurnal cycle, a factor term of day vs night was included in the models (based on solar elevation data generated using the R-package *suncalc*—positive and negative solar elevation was designated as 'day' and 'night', respectively). Lastly, in order to control for depth-effect bias in the data processing (in particular due to beam volume for SED detection), a smooth term of fish density against depth was also included in each model. The form of these models was, therefore:

$$SED_{dens} \text{ or } School.det \sim s\left(Plat_{dist},\ by = interaction\left(Plat_{ID},\ Downstream\right)\right) + Day.Night + s\left(Depth\right) \tag{4}$$

where SED_{dens} and *School.det* are the density of non-schooling fish and the probability of detecting a fish school respectively, $Plat_{dist}$ is the distance from platform, $Plat_{ID}$ is a factor variable with one level per platform, *Downstream* is a binary variable representing whether or not the datapoint is downstream from the platform, *Day.Night* is a binary variable representing whether or not the datapoint was collected during daylight hours, *Depth* is the bottom depth at the location of the datapoint, and *s()* indicates a smooth term.

To investigate the potential effect of platform weight on the trends in fish density, differences between the significant (at the $\alpha = 0.05$ level) smooth terms estimated for each platform were calculated. Platforms were sorted by ascending substructure weight, and pairwise comparisons between significant terms from 'adjacent' weights were made using a prediction matrix, X_p (Rose et al. 2012). This allowed differences and 95% pointwise confidence intervals to be estimated, and so significant differences (at the $\alpha = 0.05$ level) between the shapes of smooth terms could be identified.

As well as the models which estimated fish density trends at each platform individually,, models were built using the whole dataset (not just the data >10 km from platforms) and using an areal density of platforms in place of an absolute distance to nearest platform. These areal platform densities were calculated using the 'density kernel' function in ArcGIS with a 7 km 'search radius' (the range at which the influence of a single platform falls to zero), based on the average range of influence of platforms throughout the North Sea (Lawrence et al. 2024). These models took the form

$$SED_{dens} or\ School.det \sim s\left(Plat_{dens}\right) + Day.Night + s\left(Depth\right) \tag{5}$$

where SED_{dens} and *School.det* are the density of non-schooling fish and the probability of detecting a fish school, respectively, $Plat_{dens}$ is the local areal density of oil platforms (in platforms km^{-2}), *Day.Night* is a binary variable representing whether or not the datapoint was collected during daylight hours, *Depth* is the bottom depth at the location of the datapoint, and *s()* indicates a smooth term.

Results

Roughly 400 km of acoustic data collection was completed, which was broken down into 817950 m EDSUs, of which 4789 were within 10 km of an oil platform. Throughout the whole area, the maximum recorded areal density of non-schooling fish was 0.022 m^{-2}, and the maximum fish school NASC was 7100 m^{2} nmi^{-2}. Maximum fish density values within 10 km of platforms were lower, 0.01 m^{-2} and 3792 m^{2} nmi^{-2} for non-schooling fish areal density and fish school NASC, respectively (Fig. 1).

Models of non-schooling fish (single target) density

In the models of non-schooling fish density using a platform-level factor, fish densities were found to be higher at night (Supplementary Table S2a), and significant trends between fish density and distance from platform were evident at several platforms, in both downstream and non-downstream data (Fig. 2). Despite the relationships identified, the model only explained 12.5% of the deviance in the data.

At the smallest platform, A, (substructure weighing 730 t), in the non-downstream data, there was a slight peak in fish density at intermediate distances from platform (i.e. higher densities of fish at moderate distances to the platform with slight decrease at shorter and longer distances). In the downstream data, this trend was reversed; high densities of fish were found close to, and at longer distances from the platform, with lower densities found at intermediate distances.

At platform B (weight 1537 t), no significant trend was found in the non-downstream data, and a slight positive trend in fish density with increased distance from platform was found in the downstream data.

At platform C (of intermediate weight, 5200 t), in the non-downstream data, a slight negative trend in fish density with distance from platform was found at shorter distances (up to ~4 km from platform), but at longer ranges, this became positive.

At platform D (weight 11000 t), very slight positive trends in fish density with increasing distance from platform were found in both the downstream and the non-downstream data.

At the largest platforms, E and F (weights 12 000 and 34 000 t, respectively), strong negative trends in fish density with increasing distance from platform were found.

Pairwise comparisons of the shapes of these significant smooth terms (Rose et al. 2012), revealed significant differences between the fitted curves for each platform weight, and showed a general trend of stronger negative trends in fish density with increasing distance from platform at heavier platforms (Supplementary Fig. S3). At ranges up to ~4 km from platform, in comparisons between the smallest two platforms (5200 vs 730 t) and the largest two platforms (34 000 vs 12 400 t), a more strongly negative trend in fish density with increasing distance from platform was found (as indicated by the downward slopes in Supplementary Fig. S3). In these two comparisons, at greater distances, there was a reversal of this pattern; this was caused by the increased fish densities at the larger platforms at distances >7 km (Fig. 2), although these were less sampled areas, and there was more uncertainty about the fitted curves (particular for the largest platform) at these distances (Fig. 2). In the comparison of the curves fitted at the larger intermediate weight platforms (12 400 vs 11 000 t), there was a consistent pattern of a stronger negative trend at the larger platform. In the comparison of the smaller intermediate platforms (11 000 vs 5200 t), the only reversal of the pattern was found, with a stronger negative trend in fish density to ranges of ~5 km identified at the smaller of the two platforms.

In the model of non-schooling fish (i.e. single target) density built using the whole dataset (instead of just those collected within 10 km of platforms), and using areal platform density in place of absolute distance from platform, a general trend of higher fish densities in areas of high platform densities was found (although this was non-linear with some negative trend at low platform densities) (Fig. 3; Supplementary Table S2b). This model fit the data comparably to the model splitting the data by platform, explaining 11.3% of the deviance in the data.

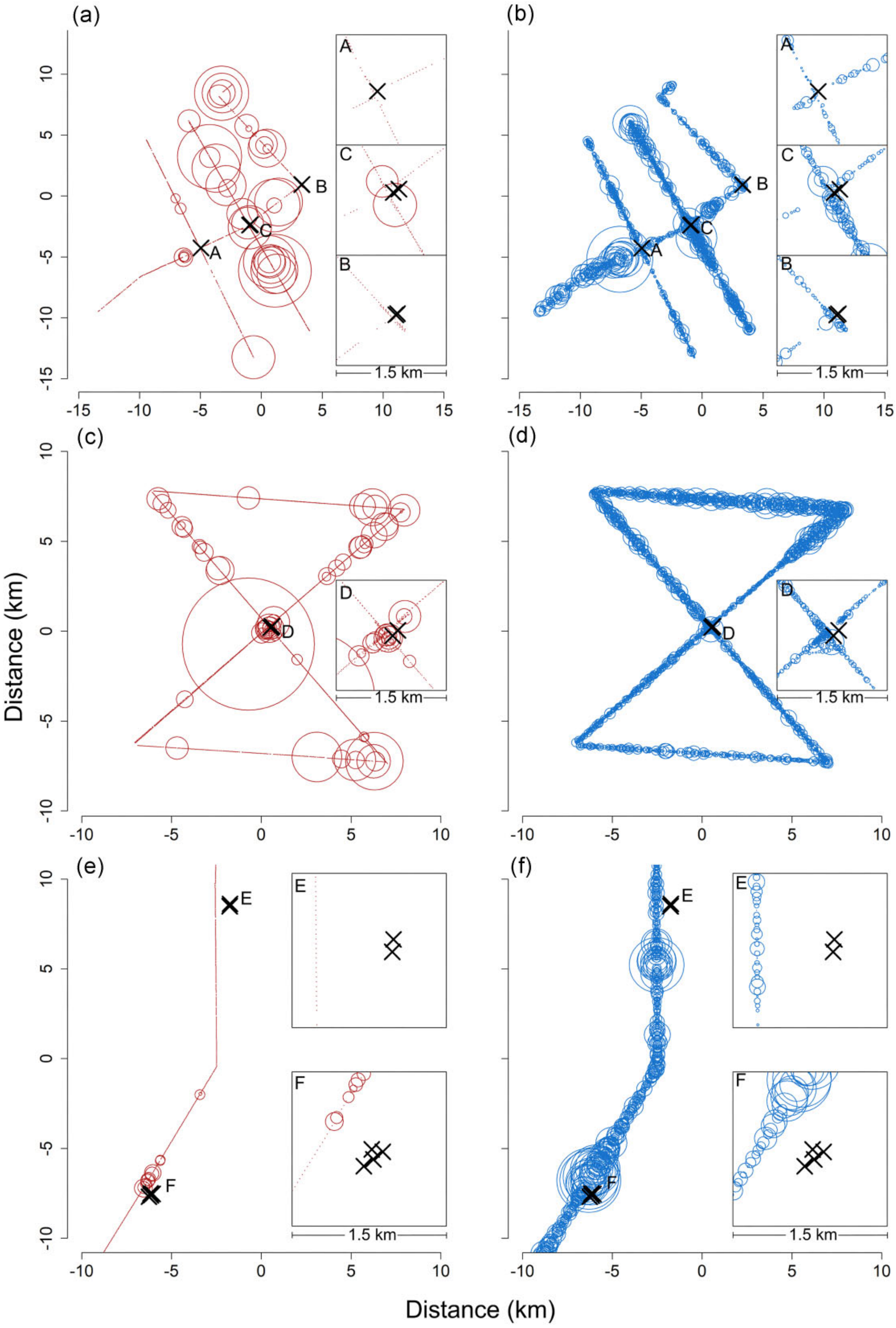

Figure 1. Maps of fish density data around the six oil platform sites. Subplots a, c, and e show fish school Nautical Area Scattering Coefficients (NASCs), with circle radius proportional to NASC (m^2 nmi^{-2}, circles) with a maximum of 3972 m^2 nmi^{-2}. Plots b, d, and f show non-schooling fish areal densities (m^{-2}, circles) with a maximum of 0.01 m^{-2}. Black crosses indicate locations of oil platforms A–F (as referred to in the text), insets show close ups of the area around platforms.

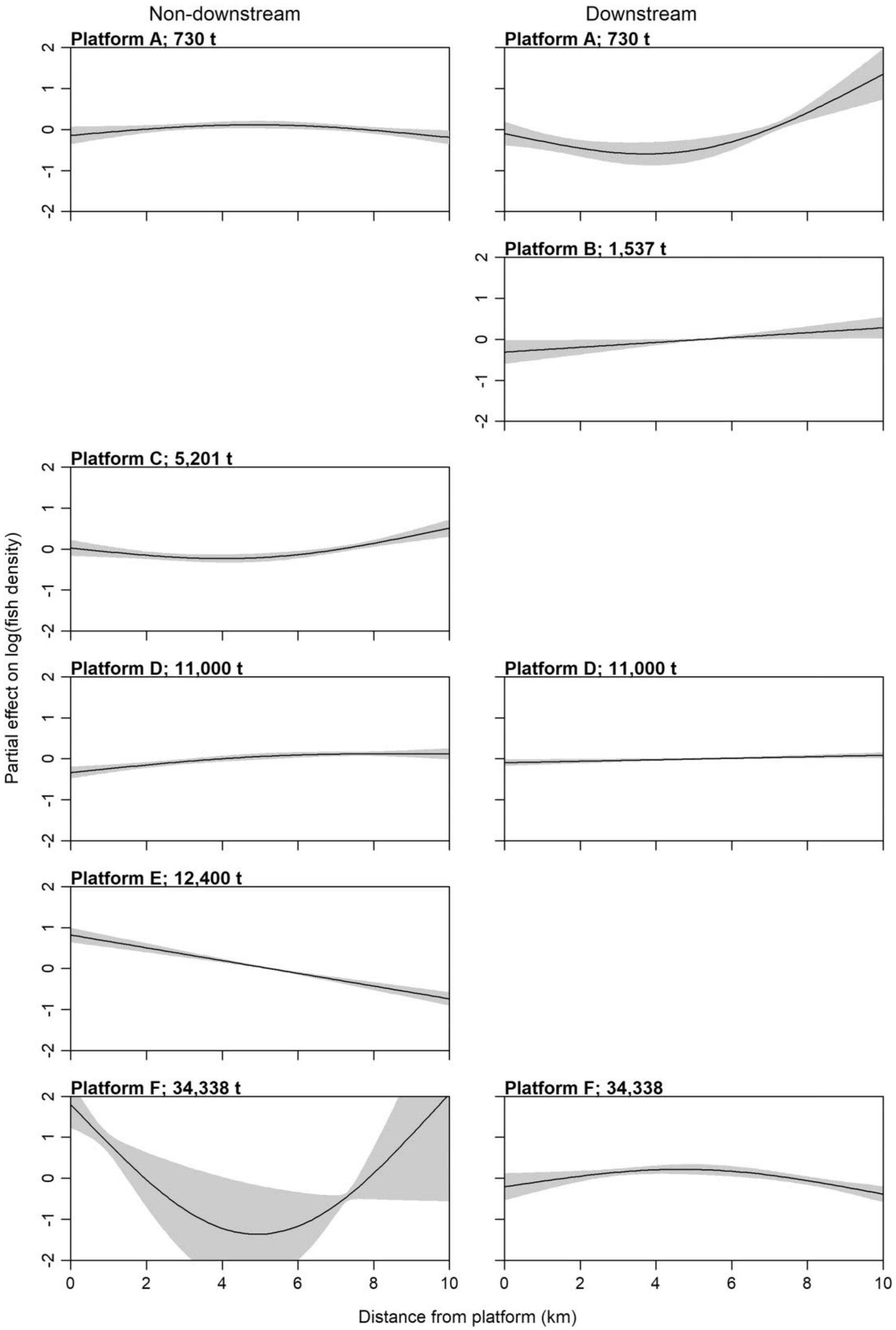

Figure 2. Plots the effect of distance from oil platform on log-transformed non-schooling fish density, from smooth terms produced during the modelling process. Plots are grouped by downstream and non-downstream (columns) and by platform (rows). Partial effects are shown (solid lines), ±2 standard errors (grey regions). Only significant relationships (at the $\alpha = 0.05$ level) are shown.

Models of fish school presence/absence

In the models of fish school presence/absence including a platform-level factor term, no difference in detection probability was found between day and night (Supplementary Table S2c), but significant relationships between fish school presence and distance from platform were evident at several platforms, in both downstream and non-downstream data (Fig. 4). This model fit the data less well than that for non-

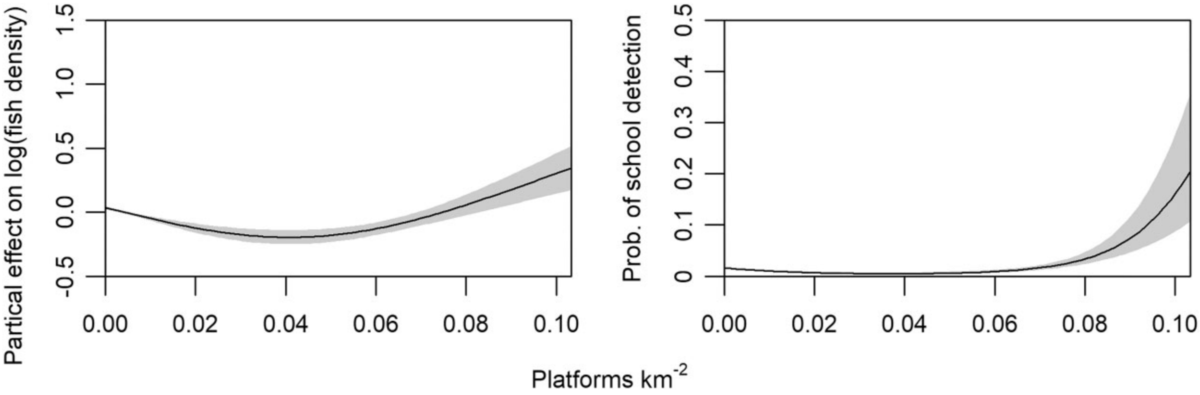

Figure 3. Plots of the partial effect of areal platform density (platforms per km^2) on log-transformed non-schooling fish density (left) and fish school detection probability (right), from smooth terms produced during the modelling process. Partial effects are shown (solid lines), ±2 standard errors (grey regions).

schooling fish, explaining just 8.3% of the deviance in the data.

At platform B, the second smallest platform (1500 t), a general positive trend in fish school detection probability was found with increasing distance from platform in the non-downstream data.

At platform C (5200 t), in the non-downstream data, a peak in fish school detection probability was found at intermediate distances (~4 km), with a lower likelihood of schools being detected at smaller and greater distances from the platform.

At platform D (11 000 t), in the downstream data, a positive trend between fish school detection probability and distance from platform was detected, while in the non-downstream data, this trend was reversed.

At platform F (34 000 t), in both the downstream and non-downstream data, a negative trend was identified in the probability of fish school detection with increasing distance from platform. At the most extreme distances from platform, >8 km, the model fit an increase in probability of school detection in the non-downstream curve, but this was accompanied by very wide confidence intervals, suggesting very high levels of uncertainty associated with this feature of the curve.

Because there was no consistent pattern in these trends to compare between the different platforms, pairwise comparisons (as per the non-schooling fish model results) were not performed.

In the model of fish school presence/absence using all the data collected (instead of just those collected within 10 km of platforms) and including areal platform density instead of absolute distance from platform, a general trend of a higher likelihood of school detection in areas of higher platform density was found (Fig. 3; Supplementary Table S2d). Despite identifying these trends, the model fit the data poorly, explaining just 3.3% of the deviance in the data.

Discussion

This study presents evidence of fish associating with oil platforms over relatively long distances (up to several kilometres from the platform). While fish have been found to associate with oil platforms elsewhere in the world, these associations have generally only been detectable over very short distances (10 to 100 s of metres from the platform structure). We found that there were detectable negative trends in fish density with increasing distance from platform (i.e. more fish were found nearer platforms) over ranges of several kilometres from oil platforms, as has previously been found around oil platforms in the North Sea (Lawrence et al. 2024). It is noteworthy, though, that these trends were not consistent between platforms, and that at some platforms, no trend in fish density was detected over any range. However, while some variability in these trends between platforms exists, the models built using all the data and the metric of areal platform density (instead of distance to nearest platform) showed both increased fish density and increased likelihood of swimbladdered fish school detection in areas with high platform density (Fig. 3) to be the general cross-platform tends. It must be noted, however, the fish school model fit the data poorly, suggesting the reported association with platforms explains only a small component of the variability in school distribution.

Due to the difficulty in establishing an accurate and representative baseline or background fish density, no attempt to determine the ‘range of influence’ was made for any platform. This is an important metric describing the range to which fish are elevated above background levels (Stanley and Wilson 1998, 2000, 2003), but requires sufficient data collected far from the influence of platforms, in otherwise comparable habitats, and so was beyond the scope of this study.

One factor that was considered as a potential driver of the observed interplatform variability in fish density trends was platform size. It was found that, for non-schooling fish, the associations between increased fish density and proximity to platform were generally stronger for platforms (or bridge-linked platform complexes) with higher substructure weight, at least at ranges out to ~5 km from platform. While some previous studies have examined the differing ecological communities or interactions recorded at several platforms, the weight of the platform has not directly been considered as a driver of this variability. The association between fish and platforms at different depths have been compared in the Gulf of Mexico, although neither depth, nor the necessarily covarying substructure weight, was investigated as a driver of the variability observed (Stanley and Wilson 1998). In waters off California, a comparison of fish assemblages across 23 oil platforms found significant changes in species composition with depth, although this was found to echo the habitat preferences of the species involved—there was no assertion that the observed differences were due to the differing sizes of the platform (Love

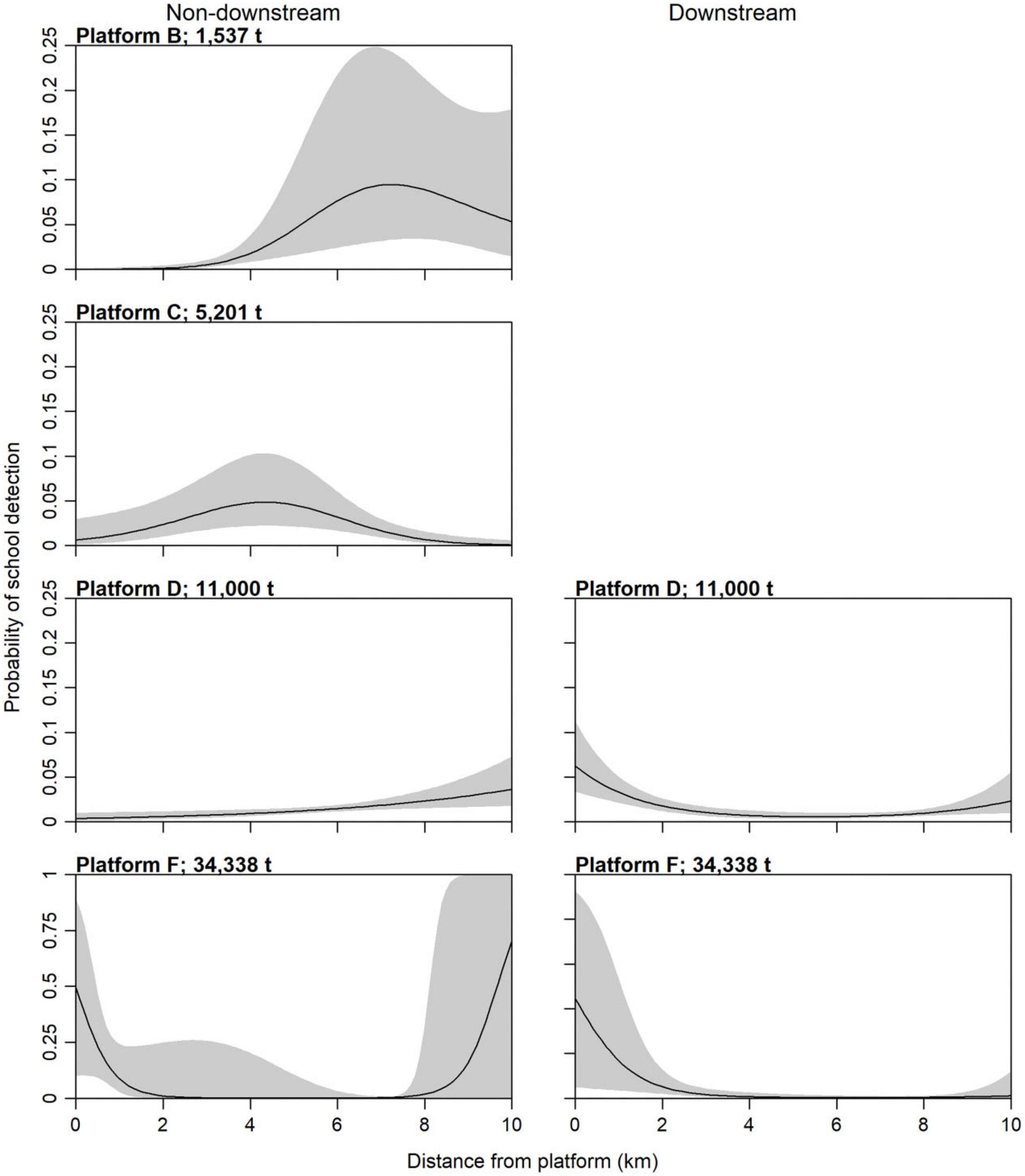

Figure 4. Plots of the effect of distance from oil platform on the probability of detecting fish schools, from smooth terms produced during the modelling process. Plots are grouped by downstream and non-downstream (columns) and by platform (rows). Partial effects are shown (solid lines), ±2 standard errors (grey regions). Only significant relationships (at the $\alpha = 0.05$ level) are shown—these were found with platform B, C, D, and F (weights 1500, 5200, 11 000, and 34 000 t, respectively, as shown in each subplot). Note the change of *y*-axis scale in the bottom row.

et al. 2019a). It was noted though, that since fixed oil platforms span the full extent of the water column, they can provide habitat for species in areas which would normally exceed the species' habitat preference. In the North Sea, one study of fish using tags and trawl survey data related fish densities to habitat variables, and used arbitrarily increasing areal buffers around platforms of increasing size class to act as proxy for an unmeasured increase in the influence larger platforms will have on their surroundings (Wright et al. 2020). While the study found seasonally varying effects of platform areal coverage on fish density, no effort to validate or examine the assumed size-dependant influence was made.

It must be noted, however, that in this study platform weight covaries with platform identity, and that there is no conclusive evidence of a causal relationship between platform weight and the strength of trend in fish density. There may be other factors associated with each platform that cause or contribute to the observed variability in trends seen here. The age of a platform will necessarily affect the extent or quality of its impacts on the local environment (Todd et al. 2018, 2020, Torquato et al. 2021). The operational status of platform will also likely affect its influence on local fauna; this status could be across the 'life-cycle' scale of a platform (e.g. there may be differences between when the platform is under construction, operational, closed down and following decommissioning), or on the short-term activity level (e.g. during or between drilling campaigns). All of these changes may influence how the platform affects its immediate environment, in terms of its output of noise, food waste, produced-water, pollutants, and light, which may all be important in shaping how local flora and fauna perceive or react to the platform's presence. More work is needed to fully understand the drivers of interplatform variability in trends of fish density reported here and elsewhere (Lawrence et al. 2024), taking into account as comprehensive a suite of platform characteristics as possible.

Despite this, it is reasonable to hypothesize that platform size appears to influence the extent or strength of the impact a platform has on the environment. Many mechanisms by which a platform physically affects the environment (by providing hard substrate or complex 3D structure, or affecting local hydrodynamics) scales with size or surface area (which scales with size, for a given platform type, e.g. fixed steel jackets). One other potential reason for an increased abundance or biomass of fish in close proximity to oil platforms in the North Sea is that these structures act as de facto marine protected areas (MPAs) due to the 500 m exclusions zones in force around them, closing the area to fishing and shipping. While the size of this area (and so, its effects) is not directly linked to substructure weight, here, we treated bridge-linked complexes as a single platform (and assigned the combined substructure weight). These would indeed have a larger exclusion zone footprint, due to the combined non-overlapping area of the exclusion zones, and so could have an increased effect as an MPA.

While the theoretical increased impacts of larger platforms are logical and clear, we present the first evidence that may suggest that larger oil platforms in the North Sea do indeed seem to have a stronger influence on the local fish populations than do smaller platforms. If a causal link can be demonstrated, this may have significant implications when considering the optimal strategy for decommissioning (Sommer et al. 2019, Birchenough and Degraer 2020, Fowler et al. 2020); if structures are to be left, in part, in the sea (e.g. in cases of derogation from OSPAR decision 98/3 (OSPAR 1998) where jackets are cut above the footings), there may be value to leaving more structure *in situ* so that the remaining influences on local populations, and other reef effects, can be maximized. More work is needed to examine this possibility further.

An additional important consideration if structures are to be left in place following decommissioning with the intent of increasing, particularly commercially important, fish numbers, is that of managing access and local exploitation around these 'artificial reefs'. In well managed areas, such as the North Sea and northeastern Atlantic (Fernandes et al. 2017), it is unlikely that local exploitation of elevated fish densities around these sites would have population level effects, assuming they comply with the current stock management plan (e.g. the total allowable catch, TAC). In less well managed areas, or areas with a high prevalence of illegal fishing, however, the existence of an artificial reef can in fact have a detrimental effect on the exploited population. Elevated and spatially focussed fishing effort, exploiting the higher catchability and locally enhanced densities of a given fish population, can causing fishing mortality to outweigh any potential benefit to the population caused by the presence of the reef (Brochier et al. 2021). This is particularly true in areas where access to the areas around artificial reefs remains open, and so management decisions about the optimal fate of these structures, and the protections afforded them if they are left in place, must be carefully considered.

It must be noted that no consistent trend was observed between distance from platform and the probability of detecting a fish school, and by extension, therefore, platform weight was not found to have an effect on this relationship. It is possible that fish school distribution is simply less affected by oil platforms than non-schooling fish, or it could be that more data are required to fully resolve the relationships. Schooling fish are, by definition, more patchy in their distributions than non-schooling fish, and so it may be that more data would be needed (increasing both spatial and temporal coverage) to capture the relationship between distance from platform and fish school occurrence (and any associated relationship with platform weight).

Little evidence was found that hydrodynamic effects are an important driver of the associations between fish and oil platforms, or of the interplatform variability in those trends. The 'downstream' variable used here did not display any consistent effect on the relationships between fish density and distance from platform, suggesting that the association between fish and platforms is not dependent upon the direction from the platform relative to the local current direction.

However, there are several potential shortcomings of the analysis of the hydrodynamic data presented here which means that the possibility of hydrodynamics playing a role in shaping these associations cannot be entirely ruled out. The hydrodynamic model used here only included data up to 2019, where the acoustic data on fish densities was collected in 2021. While efforts were made to equivalate the acoustic data timings with points in the 2019 tidal cycle (considering both spring/neap and high/low tidal cycles), it is possible that the equivalences were not perfect, or that differing current regimes occurred between years, despite an equivalent point in the tidal cycle being selected. Additionally, the use of a 45° 'downstream' segment may be insufficiently strict as a definition of downstream, and it is possible that the platform may not actually have any measurable effect on hydrodynamics at the edges of that segment. This would essentially mean 'non-downstream' data were included in the 'downstream' dataset. Furthermore, there was no consideration of current speed in the analysis, nor of the direction of the residual or prevailing current, relative to the current at the time of data collection. It is likely that the true effect of hydrodynamics on fish distributions around oil platforms, if any exists, results from the interaction between the current speed at the time of data collection, the sampling location relative to the instantaneous current direction, and how the instantaneous current direction at that moment relates to the residual current direction. Here, it is likely that data was classed as 'downstream' when either the current speed was low, or the current was 'off-axis' relative to the residual current direction. At low current speeds, data further from the platform would be less likely to experience a downstream effect, and away from the axis of the residual current, any persistent hydrodynamic effects (e.g. increased turbulence, mixing, or salinity changes) (van Berkel et al. 2020) might be weaker or absent.

More work, involving repeated surveys around platforms, throughout the tidal cycle and covering upstream, downstream, and adjacent (relative to both the instantaneous and residual current directions) areas around the platform, is needed to better understand the importance of hydrodynamics in driving the associations between fish and platforms. This work would ideally include collection of *in situ* current data which would be used either in place of, or for validating, hydrodynamic model outputs.

Furthermore, this survey was limited by the endurance of the vessel and the need to sample at multiple sites, and so no more data could be collected at each site. Future work should extend the area surveyed, to be better able to resolve a 'background' fish density, allowing for the calculation of the range of influence of the platform on local fish densities. Additionally, alternative survey designs, involving more intensive survey effort (more spokes to the 'star' design), or parallel transects should be considered as they have been found to be effective for focal point surveys previously (Doonan et al. 2003, Moreno et al. 2007, White et al. 2023).

Collection of additional, complementary datasets from a variety of potential additional sensors would also enhance the utility of future surveys. Video and stills-camera data could be used to collect information on, for example, (when deployed underwater) fish size, species composition, and behaviour (Fernandes et al. 2016, Boldt et al. 2018) or seabed habitat (Michaelis et al. 2019), and (when deployed above water) encounters with seabirds and marine mammals (Verfuss et al. 2019, Totland and Johnsen 2022). Passive acoustic equipment could also used to collected data on detection rates of vocalising marine mammals (Zimmer 2011) and, if the survey platform is sufficiently quiet, on the soundscapes around focal platforms (Johnston and Pierpoint 2017, Whitt et al. 2020, Angus et al. 2022). Indeed, it might be that high densities of fish (and other sound sensitive animals) around oil platforms are caused in part by attractive effects of irradiated noise (Clausen et al. 2021, Cresci et al. 2023).

Onboard water sampling and filtration could collect samples of eDNA. These could provide useful complementary data for more detailed analysis of the fisheries acoustic data (by providing information about the species composition of the local fish assemblage), as well as providing information about the distribution and abundance of other species, not sampled by the acoustic equipment (Yamahara et al. 2019, Preston et al. 2023).

Other important factors that may influence the effects observed in this study, but will require additional work to resolve, include potential seasonal differences in trends in fish density around oil platforms, as well as diel variations which may be influenced by the illumination of platforms at night. Seasonal variability in fish behaviour, including in feeding, spawning and migratory behaviour, may strengthen or weaken associations with oil platforms, while diel patterns in behaviour (e.g. changes in vertical distribution and feeding) may interact with the diel changes in conspicuity of platforms caused by illumination at night. Here, a day/night effect was identified, but only indicating that more individual fish were detected at night. This effect has been observed previously, and it is hypothesized that demersal fish leave the area near the seabed (where they are unavailable for detection with a vessel-mounted echosounder) and migrate into the water column to feed (Aglen et al. 1999, Godø and Michalsen 2000, Righton et al. 2001). The influence of illumination from oil platforms requires further investigation, however, and, if present, will likely be also be species-specific and depth-dependent; in some deeper areas, little light from surface illumination will reach the greater depths some species are found.

Additionally, any study of fish using vessel mounted fisheries acoustics sensors must consider the impact of the presence of the vessel on the behaviour and distribution of fish, and any potential biases the act of sampling may generate. Fish behavioural responses to survey vessels are complex and not well understood (Fernandes et al. 2000, De Robertis and Handegard 2013, Brehmer et al. 2019), however in this case, it is likely that the USV is so quiet that is would be undetectable above ambient noise levels at the ranges in question, and so would have little influence on fish behaviour. Furthermore, any behavioural changes which may have occurred, and the biases associated with them, would likely be constant throughout the survey and so the ecological trends and relationships identified are likely unaffected.

As well as the ecological insights into the association between fish and oil platforms, this work also serves to highlight the utility of USV-deployed fisheries acoustic sensors for surveying effectively in hazardous or difficult to reach areas. In this case, the waters around North Sea oil and gas platforms are protected by 500 m safety zones, which are controlled by the platform operator, and rigorous risk assessment and permitting procedures. Access to these areas with a large vessel is difficult, but the lack of risk posed to the structures by the small USV meant access could be granted with confidence, albeit still following a through risk assessment and mitigation process. The over-the-horizon, real-time control (i.e. non-autonomous) via satellite link now available on modern USVs means important fisheries acoustic data can be collected safely (for both crew, there being none, and other marine users and infrastructure), and in a low-cost, low-carbon manner.

Acknowledgements

We would like to thank the operators of the oil platforms for their assistance in the planning of the survey, and for granting access to their assets' safety zones. We would like to thank the operator and pilots of the USV for conducting the survey safely and effectively. Our thanks are also due to the anonymous reviewers whose comments and feedback greatly improved the manuscript.

Author contributions

Conceptualisation: JL, PF, DS, MH; Methodology: JL, PF, DS, MH; Formal analysis: JL; Investigation: JL, PF; Data curation: JL; Writing - original draft: JL; Writing - review and editing: PF, DF, MH; Supervision: PF; Project administration: PF; Funding acquisition: PF, DS, MH.

Supplementary data

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

Conflict of interest

The authors declare no competing interests.

Funding

The work was funded by the UK Natural Environment Research Council (NERC) as part of the FISHSPAMMS project (grant number NE/T010681/1) under the INSITE programme.

Data availability

The processed data outputs and R-code used to generate the results presented here are publicly available at https://github.com/joshua-lawrence1/XO21.

References

Aglen A, Engås E, Huse I *et al.* How vertical fish distribution may affect survey results. *ICES J Mar Sci* 1999;**56**:345–60. https://doi.org/10.1006/jmsc.1999.0449

Angus J, Bouvier-Brown M, Robinson A. Solar powered uncrewed surface vehicles (USVs) for marine protected area (MPA) monitoring. In: *OCEANS*. Hampton Roads, VA: IEEE. 2022.

Baine M Artificial reefs: a review of their design, application, management and performance. *Ocean Coastal Manage* 2001;**44**:241–59.

Barton B, De Dominicis M, O'Hara Murray R *et al.* Scottish shelf model 3.02–27 year reanalysis. 2022. https://doi.org/10.7489/12423-1

Birchenough SNR, Degraer S. Science in support of ecologically sound decommissioning strategies for offshore man-made structures: taking stock of current knowledge and considering future challenges. *ICES J Mar Sci* 2020;**77**:1075–8. https://doi.org/10.1093/icesjms/fsaa039

Boldt JL, Williams K, Rooper CN *et al.* Development of stereo camera methodologies to improve pelagic fish biomass estimates and inform ecosystem management in marine waters. *Fish Res* 2018;**198**:66–77. https://doi.org/10.1016/j.fishres.2017.10.013

Brehmer P, Sarré A, Guennégan Y *et al.* Vessel avoidance response: a complex tradeoff between fish multisensory integration and environmental variables. *Rev Fish Sci Aquacult* 2019;**27**:380–91.

Brochier T, Brehmer P, Mbaye A *et al.* Successful artificial reefs depend on getting the context right due to complex socio-bio-economic interactions. *Sci Rep* 2021;**11**:1–11.

Claisse JT, Pondella DJ, Love M *et al.* Oil platforms off California are among the most productive marine fish habitats globally. *Proc Natl Acad Sci* 2014;**111**:15462–7. https://doi.org/10.1073/pnas.1411477111

Clausen KT, Teilmann J, Wisniewska DM *et al.* Echolocation activity of harbour porpoises, phocoena phocoena, shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms. *Ecol Solut Evid* 2021;**2**:e12055.

Cresci A, Zhang G, Durif CMF *et al.* Atlantic cod (Gadus morhua) larvae are attracted by low-frequency noise simulating that of operating offshore wind farms. *Commun Biol* 2023;**6**:1–10. https://doi.org/10.1038/s42003-023-04728-y

Daewel U, Akhtar N, Christiansen N *et al.* Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. *Commun Earth Environ* 2022;**3**:1–8.

Demer DA, Berger L, Bernasconi M *et al.* Calibration of acoustic instruments. ICES Cooperative Research Report No. 326. 2015, 133.

De Robertis A, Handegard NO. Fish avoidance of research vessels and the efficacy of noise-reduced vessels: a review. *ICES J Mar Sci* 2013;**70**:34–45. https://doi.org/10.1093/icesjms/fss155

Doonan IJ, Bull B, Coombs RF. Star acoustic surveys of localized fish aggregations. *ICES J Mar Sci* 2003;**60**:132–46. https://doi.org/10.1006/jmsc.2002.1331

Echoview Software Pty Ltd. Echoview Software. 2021, https://echoview.com/. (2 July 2024, date last accessed).

Fernandes PG. Classification trees for species identification of fish-school echotraces. *ICES J Mar Sci* 2009;**66**:1073–80. https://doi.org/10.1093/icesjms/fsp060

Fernandes PG, Brierley AS, Simmonds EJ *et al.* Fish do not avoid survey vessels. *Nature* 2000;**404**:35–6. https://doi.org/10.1038/35003648

Fernandes PG, Copland P, Garcia R *et al.* Additional evidence for fisheries acoustics: small cameras and angling gear provide tilt angle distributions and other relevant data for mackerel surveys. *ICES J Mar Sci* 2016;**73**:2009–19. https://doi.org/10.1093/icesjms/fsw091

Fernandes PG, Ralph GM, Nieto A *et al.* Coherent assessments of Europe's marine fishes show regional divergence and megafauna loss. *Nat Ecol Evol* 2017;**1**:0170.

Fernandez-Betelu O, Graham IM, Thompson PM Reef effect of offshore structures on the occurrence and foraging activity of harbour porpoises. *Front Mar Sci* 2022;**9**:980388. https://doi.org/10.3389/fmars.2022.980388

Floeter J, van Beusekom JEE, Auch D *et al.* Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Prog Oceanogr* 2017;**156**:154–73. https://doi.org/10.1016/j.pocean.2017.07.003

Fowler AM, Jørgensen AM, Coolen JWP *et al.* The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. *ICES J Mar Sci* 2020;**77**:1109–26. https://doi.org/10.1093/icesjms/fsz143

Fujii T, Jamieson AJ. Fine-scale monitoring of fish movements and multiple environmental parameters around a decommissioned offshore oil platform: a pilot study in the North Sea. *Ocean Eng* 2016;**126**:481–7. https://doi.org/10.1016/j.oceaneng.2016.09.003

Godø OR, Michalsen K. Migratory behaviour of north-east Arctic cod, studied by use of data storage tags. *Fish Res*, 2000;**48**:127–40. https://doi.org/10.1016/S0165-7836(00)00177-6

Johnston P, Pierpoint C. Deployment of a passive acoustic monitoring (PAM) array from the AutoNaut wave-propelled unmanned surface vessel (USV). In: *OCEANS*. Aberdeen: IEEE, 2017, 1–4.

Jørgensen D. OSPAR's exclusion of rigs-to-reefs in the North Sea. *Ocean Coast Manage* 2012;**58**:57–61.

Kaiser MJ, Pulsipher AG. Rigs-to-reef programs in the Gulf of Mexico. *Ocean Dev Int Law* 2005;**36**:119–34.

Komyakova V, Chamberlain D, Jones GP *et al.* Assessing the performance of artificial reefs as substitute habitat for temperate reef fishes: implications for reef design and placement. *Sci Total Environ* 2019;**668**:139–52. https://doi.org/10.1016/j.scitotenv.2019.02.357

Lawrence JM, Fernandes PG. A typology of North Sea oil and gas platforms. *Sci Rep* 2022;**12**:1–7.

Lawrence JM, Speirs DC, Heath MR *et al.* Elevated fish densities extend kilometres from oil and gas platforms. *PLoS One* 2024;**19**:e0302738. https://doi.org/10.1371/journal.pone.0302738

Løkkeborg S, Humborstad OB, Jørgensen T *et al.* Spatio-temporal variations in gillnet catch rates in the vicinity of North Sea oil platforms. *ICES J Mar Sci* 2002;**59**:S294–9. https://doi.org/10.1006/jmsc.2002.1218

Love MS, Caselle JE, Snook L. Fish assemblages around seven oil platforms in the Santa Barbara Channel area. *Fishery Bulletin* 2000;**98**:96–117.

Love MS, Claisse JT, Roeper A. An analysis of the fish assemblages around 23 oil and gas platforms off California with comparisons with natural habitats. *Bull Mar Sci* 2019a;**95**:477–514. https://doi.org/10.5343/bms.2018.0061

Love MS, Kui L, Claisse JT. The role of jacket complexity in structuring fish assemblages in the midwaters of two California oil and gas platforms. *Bull Mar Sci* 2019b;**95**:597–616. https://doi.org/10.5343/bms.2017.1131

Love MS, Nishimoto MM, Snook L *et al.* An analysis of the sessile, structure-forming invertebrates living on California oil and gas platforms. *Bull Mar Sci* 2019c;**95**:583–96. https://doi.org/10.5343/bms.2017.1042

Love MS, York A. A comparison of the fish assemblages associated with an oil/gas pipeline and adjacent seafloor in the Santa Barbara Channel, Southern California Bight. *Bull Mar Sci* 2005;**77**: 101–17.

Mair AM, Fernandes PG, Lebourges-Dhaussy A *et al.* An investigation into the zooplankton composition of a prominent 38-kHz scattering layer in the North Sea. *J Plankton Res* 2005;**27**:623–33. https://doi.org/10.1093/plankt/fbi035

Meyer-Gutbrod EL, Kui L, Nishimoto MM *et al.* Fish densities associated with structural elements of oil and gas platforms in southern California. *Bull Mar Sci* 2019;**95**:639–56. https://doi.org/10.5343/bms.2018.0078

Michaelis R, Hass HC, Mielck F *et al.* Hard-substrate habitats in the German Bight (South-Eastern North Sea) observed using drift videos. *J Sea Res* 2019;**144**:78–84. https://doi.org/10.1016/j.seares.2018.11.009

Moreno G, Josse E, Brehmer P *et al.* Echotrace classification and spatial distribution of pelagic fish aggregations around drifting fish aggregating devices (DFAD). *Aquatic Living Resources* 2007;**20**:343–56. https://doi.org/10.1051/alr:2008015

OSPAR. *OSPAR decision 98/3 on the disposal of disused offshore installations.' Ministerial Meeting of the OSPAR Commission*. Sintra: OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, 1998.

Page HM, Dugan JE, Culver CS *et al.* Exotic invertebrate species on offshore oil platforms. *Mar Ecol Prog Ser* 2006;**325**:101–7. https://doi.org/10.3354/meps325101

Page HM, Zaleski SF, Miller RJ *et al.* Regional patterns in shallow water invertebrate assemblages on offshore oil and gas platforms along the Pacific continental shelf. *Bull Mar Sci* 2019;**95**:617–38. https://doi.org/10.5343/bms.2017.1155

Patterson RG, Lawson E, Udyawer V *et al.* Uncrewed surface vessel technological diffusion depends on cross-sectoral investment in open-ocean archetypes: a systematic review of USV applications and drivers. *Front Mar Sci* 2022;**8**:736984. https://doi.org/10.3389/fmars.2021.736984

Preston C, Yamahara K, Pargett D *et al.* Autonomous eDNA collection using an uncrewed surface vessel over a 4200-km transect of the eastern Pacific Ocean. *Environmental DNA* 2023;**00**:1–18.

Price DM, Robert K, Callaway A *et al.* Using 3D photogrammetry from ROV video to quantify cold-water coral reef structural complexity and investigate its influence on biodiversity and community assemblage. *Coral Reefs* 2019;**38**:1007–21. https://doi.org/10.1007/s00338-019-01827-3

R Core Team. R: a language and environment for statistical computing. 2020. https://www.r-project.org/. (2 July 2024, date last accessed).

Righton D, Metcalfe J, Connolly P. Different behaviour of North and Irish Sea cod. *Nature* 2001;**411**:156. https://doi.org/10.1038/35075667

Rogers A, Blanchard JL, Mumby PJ. Vulnerability of coral reef fisheries to a loss of structural complexity. *Curr Biol*, 2014;**24**:1000–5. https://doi.org/10.1016/j.cub.2014.03.026

Rose NL, Yang H, Turner SD *et al.* An assessment of the mechanisms for the transfer of lead and mercury from atmospherically contaminated organic soils to lake sediments with particular reference to Scotland, UK. *Geochim Cosmochim Acta* 2012;**82**:113–35. https://doi.org/10.1016/j.gca.2010.12.026

Sawada K, Furusawa M, Williamson NJ. Conditions for the precise measurement of fish target strength in situ. *J Mar Acoust Soc Japan* 1993;**20**:73–9. https://doi.org/10.3135/jmasj.20.73

Schultze LKP, Merckelbach LM, Horstmann J *et al.* Increased mixing and turbulence in the wake of offshore wind farm foundations. *J Geophys Res Oceans* 2020;**125**:e2019JC015858.

Schutter M, Dorenbosch M, Driessen FMF *et al.* Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: effects of location and depth. *J Sea Res* 2019;**153**:101782. https://doi.org/10.1016/j.seares.2019.101782

Simmonds J, MacLennan DN. *Fisheries Acoustics: Theory and Practice*. Oxford: Wiley-Blackwell, 2005, 456.

Soldal AV, Svellingen I, Jørgensen T *et al.* Rigs-to-reefs in the North Sea: hydroacoustic quantification of fish in the vicinity of a 'semi-cold' platform. *ICES J Mar Sci* 2002;**59**:S281–7. https://doi.org/10.1006/jmsc.2002.1279

Sommer B, Fowler AM, Macreadie PI *et al.* Decommissioning of offshore oil and gas structures—environmental opportunities and challenges. *Sci Total Environ* 2019;**658**:973–81. https://doi.org/10.1016/j.scitotenv.2018.12.193

Stachowitsch M, Kikinger R, Herler J *et al.* Offshore oil platforms and fouling communities in the southern Arabian Gulf (Abu Dhabi). *Mar Pollut Bull* 2002;**44**:853–60. https://doi.org/10.1016/S0025-326X(02)00085-1

Stanley DR, Wilson CA Spatial variation in fish density at three petroleum platforms as measured with dual-beam hydroacoustics. *Gulf of Mexico Science* 1998;**16**:73–82. https://doi.org/10.18785/goms.1601.11

Stanley DR, Wilson CA Variation in the density and species composition of fishes associated with three petroleum platforms using dual beam hydroacoustics. *Fish Res*, 2000;**47**:161–72. https://doi.org/10.1016/S0165-7836(00)00167-3

Stanley DR, Wilson CA. Seasonal and spatial variation in the biomass and size frequency distribution of fish associated with oil and gas platforms in the northern Gulf of Mexico. *American Fisheries Society Symposium*. New Orleans: U.S. Department of the Interior, 2003, 123–53.

Todd VLG, Lavallin EW, Macreadie PI. Quantitative analysis of fish and invertebrate assemblage dynamics in association with a North Sea oil and gas installation complex. *Mar Environ Res* 2018;**142**:69–79. https://doi.org/10.1016/j.marenvres.2018.09.018

Todd VLG, Warley JC, Todd IB. Meals on wheels? A decade of megafaunal visual and acoustic observations from offshore oil & gas rigs and platforms in the North and Irish Seas. *PLoS One* 2016;**11**:e0153320.

Todd VLG, Williamson LD, Cox SE *et al.* Characterizing the first wave of fish and invertebrate colonization on a new offshore petroleum platform. *ICES J Mar Sci* 2020;**77**:1127–36. https://doi.org/10.1093/icesjms/fsz077

Torquato F, Omerspahic MH, Range P *et al.* Epibenthic communities from offshore platforms in the Arabian Gulf are structured by platform age and depth. *Mar Pollut Bull* 2021;**173**:112935. https://doi.org/10.1016/j.marpolbul.2021.112935

Totland A, Johnsen E. Kayak Drone—a silent acoustic unmanned surface vehicle for marine research. *Frontiers in Marine Science*, 2022;**9**:986752. https://doi.org/10.3389/fmars.2022.986752

van Berkel J, Burchard H, Christensen A *et al.* The effects of offshore wind farms on hydrodynamics and implications for fishes. *Oceanography* 2020;**33**:108–17. https://doi.org/10.5670/oceanog.2020.410

van Elden S, Meeuwig JJ, Hobbs RJ *et al.* Offshore oil and gas platforms as novel ecosystems: a global perspective. *Front Mar Sci* 2019;**6**:548. https://doi.org/10.3389/fmars.2019.00548

Verfuss UK, Aniceto AS, Harris DV *et al.* A review of unmanned vehicles for the detection and monitoring of marine fauna. *Mar Pollut Bull* 2019;**140**:17–29. https://doi.org/10.1016/j.marpolbul.2019.01.009

White AL, Sullivan PJ, Binder BM *et al.* An evaluation of survey designs and model-based inferences of fish aggregations using active acoustics. *Front Mar Sci* 2023;**10**:1176696. https://doi.org/10.3389/fmars.2023.1176696

Whitt C, Pearlman J, Polagye B *et al.* Future vision for autonomous Ocean observations. *Front Mar Sci* 2020;**7**:697.

Whomersley P, Picken GB. Long-term dynamics of fouling communities found on offshore installations in the North Sea. *J Mar Biol Assoc UK* 2003;**83**:897–901. https://doi.org/10.1017/S0025315403008014h

Wood S. Package 'mgcv'; mixed GAM computation vehicle with automatic smoothness estimation. 2017. https://www.rdocumentation.org/packages/mgcv/. (2 July 2024, date last accessed).

Wright SR, Lynam CP, Righton DA *et al.* Structure in a sea of sand: fish abundance in relation to man-made structures in the North Sea.

ICES J Mar Sci 2020;77:1206–18. https://doi.org/10.1093/icesjms/fsy142

Yamahara KM, Preston CM, Birch J *et al*. In situ autonomous acquisition and preservation of marine environmental dna using an autonomous underwater vehicle. *Front Mar Sci* 2019;6:464097. https://doi.org/10.3389/fmars.2019.00373

Zimmer W. *Passive Acoustic Monitoring of Cetaceans*. Cambridge: Cambridge University Press, 2011, 368.

Handling Editor: Steven Degraer