Marine Environmental Research 204 (2025) 106959

Contents lists available at ScienceDirect

Marine Environmental Research

journal homepage: www.elsevier.com/locate/marenvrev

Increased fish abundance, biodiversity, and body size near a North Sea oil and gas platform

Bruno Ibanez-Erquiaga [a,*], Henrik Baktoft [a], Tobias K. Mildenberger [a], Jonas Teilmann [b], Lars Kleivane [c], Leandra M. Kornau [d,e], Mette D. Agersted [f], Sixten M. Hüllert [b], Jon C. Svendsen [a]

[a] National Institute of Aquatic Resources (DTU Aqua), Technical University of Denmark, Silkeborg, Denmark
[b] Section for Marine Mammal Research, Institut for Bioscience, Aarhus Universitet, Denmark
[c] LKARTS-Norway, 8290, Skutvik, Norway
[d] Wageningen Marine Research, Wageningen University & Research, Den Helder, the Netherlands
[e] Aquaculture and Fisheries Group, Wageningen University & Research, Wageningen, the Netherlands
[f] Department for Nature and Marine, WSP Denmark, 2630, Taastrup, Denmark

ARTICLE INFO

Keywords:
Artificial habitats
Marine ecology
Offshore structures
Reefs
Ecological assessment
Decommissioning
Atlantic cod
Gadus morhua

ABSTRACT

In the North Sea, offshore oil and gas (O&G) platforms must be totally removed through decommissioning at the end of their productive life. However, the role of O&G platforms in marine ecosystems, especially for fish assemblages, is not well enough defined yet. Here, we document the association between an O&G platform in the North Sea and the fish assemblages along a distance gradient of 1–600 m from the platform. Scientific angling provided data on fish biodiversity, abundance, and body size. In addition, acoustic data on fish density and target strength were collected to explore spatial and diel fish distributions. The angling data comprised 1217 fish from 11 species, with the highest fish abundance, and all species occurring, within 20 m from the platform. Platform proximity was positively associated with fish biodiversity, and total fish abundance, as well as the specific abundances of Atlantic cod *Gadus morhua*, dab *Limanda limanda*, whiting *Merlangius merlangus*, and mackerel *Scomber scombrus*. Body sizes of Atlantic cod, whiting, and mackerel were also positively associated with the platform. Absent non-native or invasive species provided no support for stepping stone scenarios. This study highlights the attraction of a variety of fish species towards O&G platforms in the North Sea. Potential local loss of marine biodiversity following full platform removal should be considered in future discussions on platform decommissioning policies.

1. Introduction

Offshore oil and gas (O&G) platforms have been operating for several decades, and thousands of platforms currently exist worldwide (Martins et al., 2023). The presence of O&G platforms impacts the marine environment in multiple ways, for example by modifying the physical composition of the habitat (Bond et al., 2018; Fowler et al., 2019). O&G platforms provide hard substrate for colonizing organisms that are food items for species of higher trophic levels. O&G platforms also increase habitat complexity and provide refuge and protection from predation, and fisheries when a fishing ban is enforced around the platform location (Bull and Love, 2019; Fowler et al., 2019). On the other hand, O&G platforms could affect fish physiology and behavior, facilitate the spread of invasive species, and pose shipping and pollution hazards (Bond et al., 2018). The effects of O&G platforms on marine ecosystems are not yet fully understood, and research is often challenged by restrictions, costs, and complex logistics (McLean et al., 2022).

Importantly, the effects of offshore O&G platforms on fish communities remain uncertain, and observations at different basins and O&G structures on fish ecology may differ. Contrasting observations may result from platform-specific factors such as surrounding habitat, structure type, depth, latitude, and human activity (Lawrence and Fernandes, 2022). For example, while oil platforms off the coast of Gabon reportedly had a locally unique fish community, fish species found at O&G platforms in the North Sea were commonly reported in the area (Friedlander et al., 2014; Ibanez-Erquiaga et al., 2024). Contrasting trends in fish productivity have also been reported at offshore O&G platforms. For instance, red snapper *Lutjanus campechanus* reproductive

* Corresponding author.
E-mail address: bruib@aqua.dtu.dk (B. Ibanez-Erquiaga).

https://doi.org/10.1016/j.marenvres.2025.106959
Received 10 June 2024; Received in revised form 7 January 2025; Accepted 8 January 2025
Available online 10 January 2025

output in the Gulf of Mexico was higher at natural reefs than at O&G platforms (Glenn et al., 2017), while the opposite trend was suggested for redfish *Sebastes* spp. in California (Claisse et al., 2019). Also, the extent of the effects of O&G platforms on fish assemblages is uncertain, with reports suggesting ranges of influence from 10 to 100 m and up to 23 km (Lawrence et al., 2024). Moreover, the potential effects on fish condition and behavior are unknown. Thus, further ecological studies at O&G platforms are warranted and may require case and species-specific assessments (Snodgrass et al., 2020).

Decommissioning is a complex process that consists of taking a platform out of service at the end of its productive life and either removing it totally, partially, or leaving it in place (Claisse et al., 2015; Fowler et al., 2014). When the structure is completely or partially removed, it is usually taken inland for scrapping (Fowler et al., 2014). Structures left partially or completely intact can be repurposed for new uses (e.g., reefing, CO_2 capture storage, mariculture) (Bull and Love, 2019; Sommer et al., 2019; Watson et al., 2023). Leaving O&G platform foundations intact in place could result in better ecological outcomes in comparison with alternative decommissioning options involving full removal, particularly in areas of inhospitable soft bottoms (Fowler et al., 2014; Friedlander et al., 2014; Knights et al., 2024). Assessments of fish abundance and biodiversity at O&G platforms become crucial in the context of decommissioning, as they could provide insights into decommissioning ecological outcomes. In California, post-decommissioning reduction in average fish biomass and somatic production was forecasted as >95% for complete removal, but only ~10% for partial removal at the site (Meyer-Gutbrod et al., 2020). In Thailand, evidence suggested that fish associated with a decommissioned O&G platform followed the structure which was relocated >100 km away for reefing (Marnane et al., 2022). However, the ecological outcomes of the multiple platform decommissioning options remain uncertain, partly due to the lack of study cases and real-life examples (Knights et al., 2024; Watson et al., 2023). At the same time, decommissioning decisions primarily depend on local policies and respond to stakeholder interests, financial impacts, and technical limitations, among other factors (Vidal et al., 2022).

In the North Sea, offshore O&G platform decommissioning policies follow a precautionary principle and require the complete removal of disused installations (OSPAR Commission, 1998). Therefore, standing O&G platforms and their associated structures eventually will have to be fully removed, even when the ecological consequences are unknown (Fortune and Paterson, 2020; Fowler et al., 2019; Martins et al., 2023). Meanwhile, active restoration efforts of marine hard-bottom habitats in the North Sea are taking place, sometimes involving the placement of rocks (Stenberg et al., 2015; Støttrup et al., 2017) or flat oysters (Didderen et al., 2020). The increasing interest in habitat restoration may benefit from offshore structures to reach regional environmental targets, following the revision of decommissioning policies (Ounanian et al., 2020). A global horizon scan exploring research priorities for platform decommissioning highlighted the necessity to understand the influence of offshore O&G infrastructure on the movement patterns of species and the potential post-decommissioning changes (Watson et al., 2023). An essential step toward understanding platform ecology is describing the associated marine communities and their spatial extent (Sih et al., 2022).

This study explored spatial changes in fish biodiversity, abundance, and body size at increasing distances from a platform to understand the potential role of offshore O&G platforms on fish assemblages. This study used a systematic sampling approach, providing fisheries-independent fish abundance data along a distance gradient from an O&G platform in the Danish North Sea. We hypothesized that the O&G platform is positively associated with fish biodiversity, as well as fish abundance and fish body lengths. This study aims to supply knowledge about fish ecology at O&G platforms in the North Sea, and to provide insights that could inform the debate on decommissioning policy consequences.

2. Materials and methods

2.1. Study area

The study was conducted in July and August 2023 at an oil and gas (O&G) field in the Danish North Sea about 200 km off the coast of Jutland, in western Denmark (Fig. 1). Within the O&G field, one 4-legged steel jacket platform operational for >40 years was selected for the study. The depth was 40 m, the seabed was flat, mainly composed of sand and mud, and the local habitat was classified as circalittoral sand (EMODnet, 2024). The manned platform was surrounded by a 500 m radius no-fishing zone.

2.2. Sampling design

Catch data from scientific angling at increasing distances from the platform were used to explore the association of platform foundations with fish biodiversity, abundance, and body size. Adapting from previous studies, the systematic sampling consisted of angling with rod and line 1 m above the seabed during 20-min intervals per sampling station (Reubens et al., 2013a). The catch, time of the day, coordinates, and exact fishing duration were recorded. Sampling stations were defined at 1, 10, 20, 30, 40, 50, 100, 300, and 600 m away from the platform, totaling 16–18 sampling stations per distance. Each station was sampled 16–18 times, during daylight, with standardized fishing gear (300 g metal lures with 3 hooks and 3 single hooked rubber lures above). The sampling was done by six similarly skilled fishers to reduce confounding effects. All the fish caught were frozen at −20 °C on the ship and transported frozen to a laboratory for weighing (±1 g), measuring (±1 mm), and species identification.

For the acoustic sampling, two systems (EK80 and WBAT) were applied to investigate fish spatial and temporal distribution patterns and target size near the platform. A portable acoustic sampling echosounder system (EK80, Simrad) measuring at 70 kHz (narrowband), was used to collect spatial acoustic data of fish at the angling stations and on transects from a RIB-boat travelling at 2 knots. The transducer was lowered down to ~1 m depth. Acoustic data were collected using the maximum ping rate, resulting in a ping interval of 0.2 s^{-1}. The other acoustic sampling was conducted using an autonomous acoustic system (WBAT, Simrad) also measuring at 70 kHz. The WBAT was deployed at 0 m, 50 m, and 300 m from the platform on the sea floor measuring from ~36.5 m depth and up towards the surface for 24 h at each distance. CTD profiles were collected using a CastAway mini CTD (SonTek) before the acoustic systems were deployed to compare with reflections from potential thermoclines and haloclines.

2.3. Data analysis

Angling catch data were analyzed using generalized additive mixed models (GAMM) to assess the association between distance to the platform and fish biodiversity, abundance, and body size (Wood, 2017). Species richness (number of species, *S*), Shannon-Wiener diversity index (H'), and Pielou's evenness index (J') were used as proxies of fish biodiversity (Bilous et al., 2022; Friedlander et al., 2014). Species richness represents a direct count of the number of species in a community (Colwell, 2009), Shannon-Wiener diversity index measures biodiversity based on species richness and relative abundance (Shannon, 1948), and Pielou's evenness index provides a measurement of how evenly the number of individuals are distributed among species (Pielou, 1966). Number of individuals caught per hour (catch per unit effort - CPUE) was used as an index of fish abundance (Buyse et al., 2022; Wilber et al., 2018). Fish biodiversity and abundance models were based on the full data set, including all species (total catch). Species-specific models of abundance and body size were fitted to the data for cod *Gadus morhua*, dab *Limanda limanda*, saithe *Pollachius virens*, whiting *Merlangius merlangus*, and mackerel *Scomber scombrus*. Data on distance

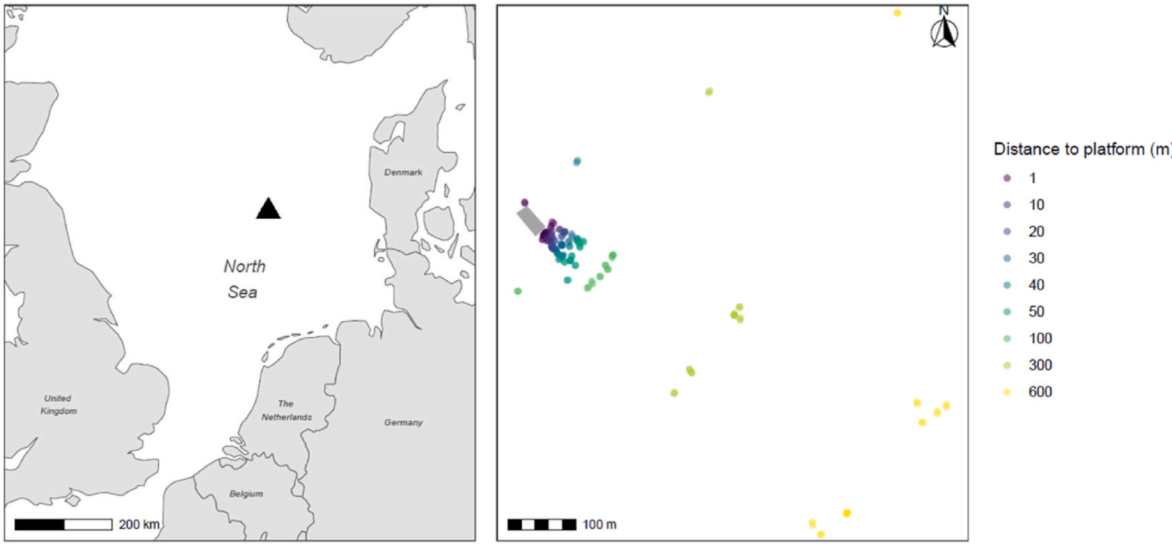

Fig. 1. Left: map of the North Sea showing the study area (black triangle). Right: study area with the oil and gas platform (grey rectangle), and the sampling stations (colored dots). The colors represent the distance between the platform and the sampling stations. The coordinates are not disclosed. The geographical extent of the sampling stations was restricted by safety concerns and any sampling in the area to the north-west of the platform was banned. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

to the platform, coordinates (latitude and longitude), time of the day, fisher, and duration were available for inclusion in the models and tested as covariates throughout the modeling process.

For biodiversity models, the total catch data were used to calculate species richness (*S*), Shannon-Wiener diversity index (*H'*), and Pielou's evenness index (*J'*). GAMMs were fitted for each proxy as the response variable using negative binomial (*S*), Tweedie (*H'*), and quasibinomial (*J'*) distributions. Fitted biodiversity models used coordinates (two-dimensional spline of latitude and longitude, i.e., interaction term '*s (Latitude, Longitude)*') as the main term (hereafter 'spatial GAMMs'). For abundance models, fish abundance entered the models as the response variable. The total and species-specific fish abundance were modeled using zero-inflated GAMMs (Binomial distribution for the presence/absence, Gaussian distribution for positive observations) due to observed patterns in the proportions of zeroes in the data (Vandeperre et al., 2019). The abundance models used coordinates as the main term (spatial GAMMs), except for *Pollachius virens*, for which the more complex spatial GAMM did not converge, and a simpler model with the distance to platform (hereafter 'distance GAMMs') instead of the two-dimensional spatial component (i.e., interaction term '*s(Latitude, Longitude)*') was used. For fish body size models, GAMMs using Gaussian distribution were fitted with total length (cm) as the response variable and distance to platform as the main term (distance GAMMs). The sampling time of the day (hours from midnight) entered all models as a cyclic covariate (Bond et al., 2018). Fisher ID entered the models as a random effect to account for potential variability introduced by the individual fishers. To account for differences in sampling effort (the duration of each sampling), we included the duration (minutes) as an offset term. The fitted models were used to predict response values for a spatial grid defined by a polygon around the fishing locations (spatial GAMMs) or as a function of the distance from the platform (distance GAMMs) (Zuur and Ieno, 2016). To account for estimated spatial variability, response variables of spatial GAMMs were displayed as a function of the distance from the platform by averaging predictions across multiple grid cells that fall within the same distance interval.

The modeling process sequentially involved data exploration, model selection, and model validation (Zuur and Ieno, 2016). Data exploration was used to identify non-linear trends, an elevated proportion of zeroes, collinearity between covariates, outliers, and interactions. Comparisons between nested models using Akaike Information Criteria (AIC) were used to define the minimum best model (lowest AIC, simpler model). Residual plots were used for model validation to diagnose overdispersion, quantile deviation, residual patterns with covariates, zero inflation, outliers, and spatial autocorrelation. All statistical analyses were performed in R program version 4.3.2 (R Development Core Team, 2023) and RStudio version 2023.12.1 (RStudio Team, 2024). Biodiversity proxies (*S*, *H'*, *J'*) were calculated using 'vegan' R package (Oksanen, 2010). GAMMs were fitted using Restricted Maximum Likelihood estimation with R package 'mgcv' (Wood, 2017).

Acoustic data were processed using the software LSSS (Large Scale Survey System, Korneliussen et al., 2006). Backscattering from targets was exported from LSSS as Nautical Area Scattering Coefficient (NASC; sA, m^2 nmi^{-2}) in 1-m depth bins using a Mean Volume Backscattering Strength (Sv, dB re 1 m^{-1}) threshold of −82 dB. Exported sA data were further processed and plotted using R program version 4.3.2 (R Development Core Team, 2023) and RStudio version 2023.12.1 (RStudio Team, 2024). Single targets were detected by applying a single echo detection algorithm in LSSS (Ona, 1999; Supplementary Table 1). The single echo detection algorithm was applied to acoustic data covering 4 min per station.

3. Results

The total catch consisted of 1217 fish individuals comprising 11 species and six families (Table 1). The sampling identified no invasive or non-native fish species. All identified fish species were known to exist in the North Sea. Of the total number of species, 82% (n = 9) were caught at 1 m from the platform and 100% of species (n = 11) within 20 m of the platform. Further, 36% (n = 4) of the species were present up to 300 m from the platform, and only 18% (n = 2) up to 600 m (outside the 500 m no-fishing zone). Five representative species accounted for most (97%; n = 1176) of the total catch. The representative species were mackerel *Scomber scombrus* (56%; n = 681), whiting *Merlangius merlangus* (12%; n = 147), Atlantic cod *Gadus morhua* (12%; n = 144), dab *Limanda limanda* (10%; n = 124), and saithe *Pollachius virens* (7%; n = 80).

3.1. Fish biodiversity

Biodiversity as species richness (*S*), Shannon-Wiener diversity index (*H'*), and Pielou's evenness index (*J'*) increased non-linearly towards the

Table 1
Summary of the total catch with species-specific abundance (number of individuals), mean and standard deviation of total length (cm), mean and standard deviation of weight (g), reported habitat type (Ballerstedt, 2008; Froese and Pauly, 2024; NOAA - National Oceanic And Atmospheric AdministrationU.S. Department Of Commerce, 2024), and the occurrence range along the distance gradient from the platform (1–600 m).

Species	Family	Abundance (no. ind.)	Mean total length (cm)	Mean weight (g)	Habitat type	Occurrence range (m)
Scomber scombrus(Mackerel)	Scombridae	681	33.3 ± 3.4	330.0 ± 102.5	Pelagic-neritic, oceanodromous, shelf areas.	1–600
Merlangius merlangus (Whiting)	Gadidae	147	27.0 ± 3.2	162.4 ± 64.9	Benthopelagic, oceanodromous, mainly mud and gravel bottoms, also sand and rock.	1–600
Gadus morhua(Atlantic cod)	Gadidae	144	39.7 ± 9.7	791.8 ± 555.2	Benthopelagic, oceanodromous, rocky bottoms, and complex habitats (e.g., boulders, seagrass).	1–100
Limanda limanda(Dab)	Pleuronectidae	124	24.7 ± 3.5	154.0 ± 75.1	Demersal, oceanodromous, sandy bottoms.	1–300
Pollachius virens(Saithe)	Gadidae	80	35.1 ± 4.9	483.7 ± 239.0	Demersal, oceanodromous, various bottoms (e.g., sand, mud, rocks, vegetation).	1–50
Melanogrammus aeglefinus (Haddock)	Gadidae	17	334.0 ± 4.5	364.8 ± 123.6	Demersal, oceanodromous, rock sand, gravel, or shell bottoms.	1–100
Eutrigla gurnardus(Grey gurnard)	Triglidae	11	23.3 ± 3.6	98.7 ± 5.0	Demersal, mostly sand bottom, sometimes rock and mud bottoms.	20–300
Pollachius pollachius (Pollock)	Gadidae	9	44.8 ± 7.8	1027 ± 487.3	Benthopelagic, oceanodromous, hard bottoms mostly, also sand.	1–10
Myoxocephalus scorpius (Shorthorn sculpin)	Cottidae	2	26.6 ± 0.3	328.0 ± 75.0	Demersal, benthic, rocky bottoms with sand or mud, or among seaweeds.	1–40
Trachurus trachurus(Horse mackerel)	Carangidae	1	33.5	328.0	Pelagic-neritic, oceanodromous, sandy bottom.	10
Trisopterus luscus(Pouting)	Gadidae	1	30.0	385.0	Benthopelagic, oceanodromous, mixed rock and sand bottoms, wrecks.	1

studied platform (Supplementary Fig. 1). The highest mean values of the biodiversity ($S = 3.11 \pm 1.37$; $H' = 0.84 \pm 0.41$; $J' = 0.76 \pm 0.25$) were observed at 1 m from the platform (Supplementary Table 2). The lowest mean biodiversity values ($S = 0.5 \pm 0.52$; $H' = 0$; $J' = 0$) were observed at 300 m from the platform. Further, mean values of biodiversity decreased >5-fold (S), 14-fold (H'), and >8-fold (J') between 1 m and 600 m from the platform.

The three models for fish biodiversity (S, H', and J') identified statistically significant associations ($p < 0.01$) between fish biodiversity and the spatial term (coordinates – latitude, longitude) (Table 2). The best minimum models excluded the cyclic term 'time of the day'. Model validation found no violation of model assumptions (Supplementary Figs. 2–4).

Spatial predictions of biodiversity indices (S, H', and J') were highest near the platform (Fig. 2). Predicted values at spatial points 1 m from the platform were 4-fold (S), 10-fold (H'), and >6-fold (J') higher than at 600 m (Fig. 3). Predicted S decreased from 2.62 at 1 m from the platform to a minimum of 0.66 at 600 m. Similarly, predicted mean values of H' decreased from 0.65 at 1 m to 0.06 around 380 m from the platform. Finally, the predicted J' values decreased from 0.66 at 1 m to 0.07 at around 300 m.

3.2. Fish abundance

Overall, fish abundance was highest within 10 m from the platform and decreased with distance. Non-linear spatial trends of fish abundance were observed for total fish abundance (all species) and the species included in the analyses (cod, dab, saithe, whiting, and mackerel) (Supplementary Fig. 5). Sampling stations next to the platform (1–10 m) had >10-fold higher abundance than those further away (300–600 m). The highest mean abundance was observed at 10 m (54.3 ± 34.5 fish/hour), followed by 1m (43.7 ± 23.4 fish/hour). The lowest mean abundance occurred at 300 m (2.2 ± 3.1 fish/hour), followed by 600 m (4.0 ± 4.8 fish/hour) (Supplementary Table 2).

The zero-inflated model for total fish abundance (Gaussian DE = 69.6%, Binomial DE = 58.3%) showed an association with the O&G platform with a statistically significant ($p < 0.01$) effect of the spatial term (coordinates) and time of the day (Table 3). Similarly, the species-specific zero-inflated models showed a statistically significant ($p < 0.01$) association of the spatial term with the abundance of cod (Gaussian DE = 50.8%, Binomial DE = 26.7%), dab (Gaussian DE = 51.6%, Binomial DE = 22.9%), whiting (Gaussian DE = 70.1%, Binomial DE = 27.3%), and mackerel (Gaussian DE = 37.8%, Binomial DE = 60.4%) (Supplementary Table 3). On the other hand, the selected model for saithe (Gaussian DE = 29.2%, Binomial DE = 36.1%) did not support ($p > 0.1$) an influence of the distance to the platform or the time of the day

Table 2
Parameters and output of the generalized additive mixed models (GAMM) of fish biodiversity (species richness S, Shannon-Wiener diversity index H', Pielou's evenness index J') at the studied oil and gas platform. The smooth term consisted of the spatial term coordinates ('Lon, Lat' – spatial GAMM). An asterisk (*) represents statistical significance ($p < 0.05$).

Model	Family	Goodness of fit, parametric coefficients	Smooth terms	Number of knots	Effective degrees of freedom	F-value/ Chi-Square	p-value
Species richness (S)	Negative binomial	Adjusted $R^2 = 0.37$; Deviance explained = 42.7%; REML = 229.3. Intercept: estimate = 0.55; standard error = 0.07; t-value = 8.2; p-value <0.01.	s(Lon, Lat)	20	6.3	46.4	<0.01*
Shannon-Wiener diversity index (H')	Tweedie	Adjusted $R^2 = 0.29$; Deviance explained = 37.3%; REML = 117.2. Intercept: estimate = −1.13; standard error = 0.13; t-value = −8.7; p-value <0.01.	s(Lon, Lat)	20	6.9	1.8	<0.01*
Pielou's evenness index (J')	Quasibinomial	Adjusted $R^2 = 0.34$; Deviance explained = 34.3%; REML = 46.4. Intercept: estimate = −0.37; standard error = 0.18; t-value = −2.1; p-value <0.05.	s(Lon, Lat)	20	7.2	2	<0.01*

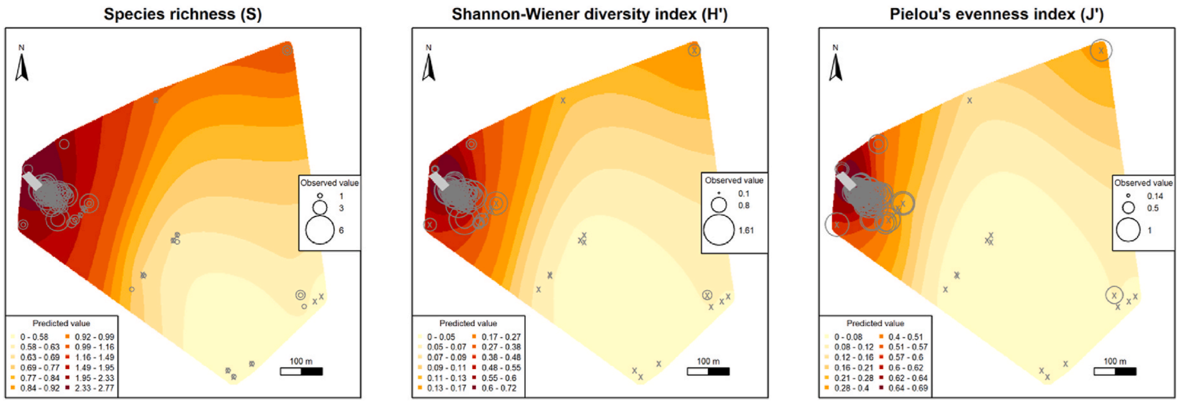

Fig. 2. Spatial prediction of biodiversity values (species richness *S*, Shannon-Wiener diversity index *H′*, and Pielou's evenness index *J′*) from fitted spatial generalized additive mixed models (spatial GAMMs). The grey rectangle represents the studied O&G platform. The color gradient represents the continuous variation of predicted value from highest (red) to lowest (yellow) for *S* (left), *H'* (center), and *J'* (right). The predicted values correspond to a 20-min sampling effort. Circle sizes represent observed values. Observations of value zero are represented with an 'x'. The coordinates are not disclosed. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

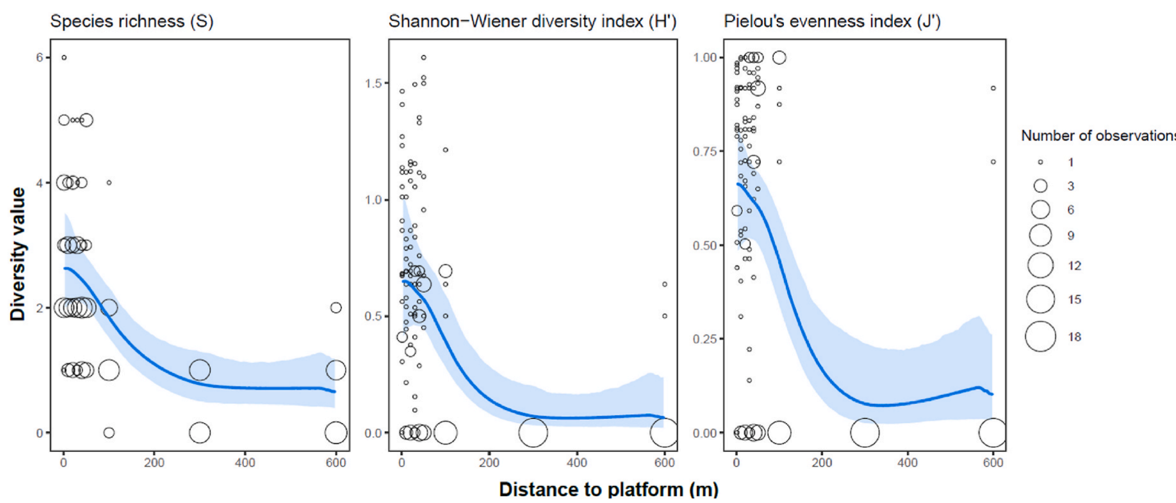

Fig. 3. Predicted biodiversity values (species richness *S*, Shannon-Wiener diversity index *H′*, and Pielou's evenness index *J′*) from the fitted spatial generalized additive mixed models (spatial GAMMs) along the distance gradient from the studied platform. The distance estimations are derived from the spatial GAMM coordinates. The panels show predicted values (blue curve), 95% confidence intervals (light blue shade), observed values (circles), and the frequency of a particular observed value (circle size) for *S* (left), *H'* (center), and *J'* (right). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

on saithe abundance. Model validation found no violation of model assumptions (Supplementary Figs. 6–11).

Overall, predicted fish abundance was higher close to the platform (Fig. 4). For whiting, the predicted fish abundance first decreased with increasing distance from the platform eastwards up to ~300 m to then increase again towards 600 m. Predicted total fish abundance (all species) was the highest (17.6 fish) at 1 m from the platform, and steeply decreased 11-fold reaching a minimum (1.59 fish) at 300 m (Fig. 5). Similarly, the species-specific predicted abundances showed steep declines between 1 m and 600 m from the platform for cod (6.98–0.01 fish), dab (1.96–0.11), and saithe (2.53–0). The trends of predicted fish abundance for whiting and mackerel were more complex with maximum values near 30–60 m from the platform and increasing uncertainty over distance.

3.3. Fish sizes

The data showed a non-linear increase in fish body size (total length in cm) towards the platform for cod, whiting, and mackerel (Supplementary Fig. 12). No consistent pattern was observed for dab, and observations of saithe beyond 10 m from the platform were insufficient to identify a pattern. The highest mean body sizes were observed at 1 m from the platform for cod (42.83 cm), dab (26.73 cm), and whiting (29.43 cm), at 10 m for mackerel (34.04 cm), and 20 m for saithe (49.5 cm) (Supplementary Table 4). Observed mean sizes along species range from the platform decreased by > 10 cm for cod (1–50 m), and >5 cm over 1–600 m from the platform for mackerel and whiting.

Species-specific body size models were fitted for cod (DE = 23%), whiting (DE = 20.2%), and mackerel (DE = 12.9%) (Table 4, Supplementary Figs. 13–15). The distance from the platform was statistically significantly ($p < 0.01$) associated with body size for cod, whiting, and mackerel. The minimum best model included the time of the day for cod and mackerel but was only significantly associated with body size for mackerel ($p < 0.01$). The models for dab and saithe could not pass model validation due to overdispersion, quantile deviations, and the presence of outliers (Supplementary Figs. 16–17).

Predicted fish body size values were overall lower at greater distances from the platform for cod, whiting, and mackerel (Fig. 6). Predicted values for whiting declined up to 300 m from the platform to then increase towards 600 m, with larger uncertainty at greater distances.

Table 3
Parameters and output of the generalized additive mixed models of the association of fish abundance (number of individuals caught per hour) with the oil and gas (O&G) platform (spatial term coordinates 'Lon, Lat'). An asterisk (*) represents statistical significance ($p < 0.05$).

Species	Family	Goodness of fit, parametric coefficients	Smooth terms	Number of knots	Effective degrees of freedom	F-value/Chi-Square	p-value
All species	Gaussian	Adjusted $R^2 = 0.63$; Deviance explained = 69.6%; REML = 136. Intercept: estimate = −1.2; standard error = 0.1; t-value = −15.4; p-value <0.01.	s(Lon, Lat)	20	12.6	11.5	<0.01*
			s(time of the day)	24	2.3	1.4	<0.01*
	Binomial	Adjusted $R^2 = 0.53$; Deviance explained = 58.3%; REML = 36.3. Intercept: estimate = 0.6; standard error = 0.72; z-value = 0.84; p-value <0.4.	s(Lon, Lat)	20	7.5	30.1	<0.01*

The highest predicted fish body sizes occurred at 1 m from the platform for cod (42.37 cm), whiting (28.56 cm), and mackerel (33.47 cm) (Supplementary Table 4). At the end of the distance range from the platform of each species, predicted fish body size values were >13 cm smaller for cod (1–50 m), and >5 cm smaller for whiting and mackerel (1–600 m). Predicted values from fish body size models that could not be validated (dab and saithe) were not included (Supplementary Fig. 18).

3.4. Spatial and diel acoustic backscattering

A combined thermocline and halocline (pycnocline) was present throughout the study period at around 23 m depth, which was also observed in the echograms (Fig. 7, Supplementary Fig. 19). The acoustic backscatter (nautical area scattering coefficient (sA; $m^2\ nmi^{-2}$)) for the whole water column (2–40 m depth) was higher closer to the platform. At distances >100 m, occasional larger fish targets were detected, while closer to the platform, fish appeared more abundant (see arrows in Fig. 7, Supplementary Fig. 20).

Overall, there were higher numbers of smaller targets (TS < −40 dB) than larger targets (TS > −40 dB) along the entire distance gradient from the platform (Supplementary Fig. 21, Supplementary Tables 5–6). Larger targets were mostly detected closer to the platform, peaking with 88 larger targets detected at 40 m distance and only on average 1.3 larger targets (TS > −40 dB) at distances >100 m from the platform. The larger targets (likely fish with a swim bladder, e.g. Atlantic cod), occurred mainly at depths from 30 to 40 m (Supplementary Table 5). The diel acoustic backscatter using the WBAT showed similar patterns at 0 m and 50 m from the platform, with higher activity around the pycnocline, especially during the night (from around 22:00 until 02:30). Stronger backscatter (i.e. more biological activity) in the water column was also observed at night compared to daytime, with fish shoals detected only at night (Fig. 8). At 300 m from the platform, the scattering layers associated with biological activity were weaker than at 0 and 50 m from the platform (Fig. 8, Supplementary Figs. 22–23). No relevant observations could be made from surface waters as wind and wave noise challenge the identification of biological signals.

4. Discussion

Understanding the potential ecological consequences of offshore oil and gas (O&G) platform decommissioning options requires knowledge of platform ecology at various scales. Further, uncovering the association between offshore platforms and motile species of commercial value such as fish will inform decommissioning policy discussions and highlight specific research needs towards better ecological outcomes. Here, we found positive associations between an O&G platform in the North Sea and fish biodiversity, abundance, and body size using systematic sampling along a distance gradient and supported by acoustic surveys. This study is among the first to explore spatial patterns of fish biodiversity using scientific angling adjacent to an O&G platform in the North Sea. Our results suggested that the platform hosts fish assemblages characterized by significantly higher biodiversity and abundance in comparison to areas away from the structure. Importantly, the platform seems to support commercially valuable fish species (e.g., saithe *Pollachius virens*, dab *Limanda limanda*) including overfished species (Atlantic cod *Gadus morhua*), occasionally at sexually mature body sizes. The results also suggested that fine-scale spatial trends of fish abundance and body size are species-specific. Our findings provide information to help clarify the potential effects of standing offshore O&G platforms on the marine environment.

We observed the highest fish biodiversity at 1 m from the platform, followed by a steep decrease reaching an asymptotic minimum at 300 m. The elevated biodiversity values suggested that the platform is a relatively rich habitat (species richness, Shannon-Wiener diversity) with a balanced community structure (Pielou's evenness) compared to the adjacent sampled areas. The observed trends in fish biodiversity

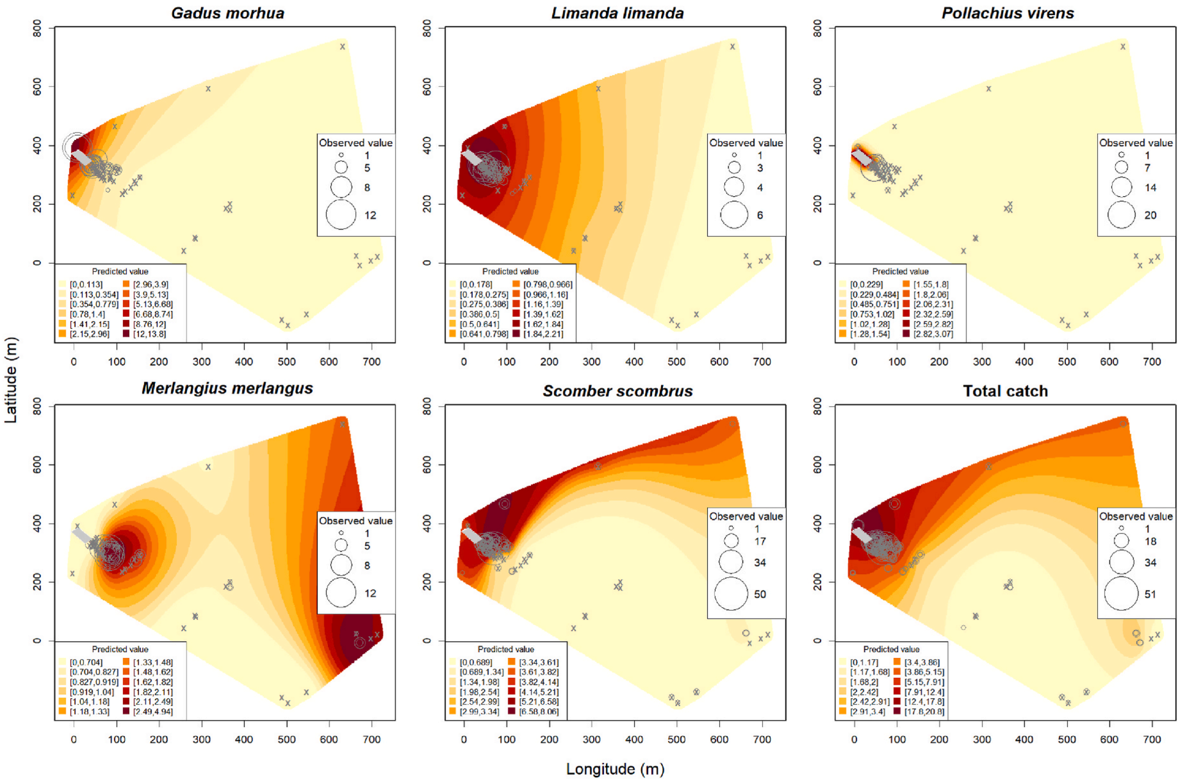

Fig. 4. Spatial prediction of fish abundance from the fitted spatial generalized additive mixed models (spatial GAMMs). The grey rectangle represents the studied O&G platform. The color gradient represents the continuous variation of predicted abundance from highest (red) to lowest (yellow) for cod *Gadus morhua*, dab *Limanda limanda*, saithe *Pollachius virens*, whiting *Merlangius merlangus*, mackerel *Scomber scombrus*, and the total catch (all species). The predicted values correspond to a 20-min sampling effort. Circle sizes represent observed values. Observations of value zero are represented with an 'x'. The coordinates are not disclosed. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

complement previous studies describing offshore platforms as biodiversity hotspots in Australia (Van Elden et al., 2022), Gabon (Friedlander et al., 2014), and Thailand (Harvey et al., 2021). However, the methods employed in these studies differ from ours and could influence the patterns observed. Higher demersal fish biodiversity and unique species composition were observed using baited underwater video at an O&G platform in comparison with control sites at a neighboring sandy seabed and a natural reef in Australia (Van Elden et al., 2022). Similarly, unique fish assemblages were observed using underwater visual censuses at O&G platforms in Gabon with 34% of species being new records for the country, and 6% for the region (Friedlander et al., 2014). In the Gulf of Thailand, an underwater video census found five fish species at reference sites 5 km away from O&G platforms and 43 species at the structures (Harvey et al., 2021). The mechanisms behind the spatial patterns of biodiversity reported here and in the literature usually include reef effects, increased seabed stability, and protection from fisheries. O&G platforms can host fish by facilitating foraging, schooling, and shoaling (Tassetti et al., 2020; Van Elden et al., 2022). Increased habitat complexity (e.g., seabed rugosity or tortuosity) and hard substrate provisioning by O&G platforms in otherwise homogeneous areas dominated by soft sediment may increase fish biodiversity, especially of demersal and benthic species (Fowler et al., 2019; Friedlander et al., 2014; Van Elden et al., 2022). The occurrence of unique fish species suggests that O&G platforms may act as islands surrounded by relatively featureless landscapes, but could also work as stepping-stones for invasive species (Friedlander et al., 2014). In the present study, no non-native or invasive species were detected, which could be due to the sampling strategy failing to target them, or due to no stepping-stone effects at the platform. Commercial species have been reported at O&G platforms and may be benefiting from the fishing restrictions around these structures, especially in areas of intense fishing pressure (Harvey et al., 2021; Tothill et al., 2024). In the North Sea, the commercially valuable Atlantic cod has been overfished for decades and the populations are currently near historically low levels (ICES, 2022). We observed Atlantic cod mainly near the platform, in contrast with previous studies using nets (Løkkeborg et al., 2002) and hydroacoustics (Soldal et al., 2002), which reported wider distribution gradients. Telemetry studies at offshore wind farms suggest that cod individuals have strong site fidelity and residency, staying within 50 m from the structures, but migrating during winter outside of the wind farm area (Berges et al., 2024; Reubens et al., 2013b). Our contrasting results on cod range could therefore be linked to the relatively lower sampling effort in the present study, which likely limited the detection of cod individuals at greater spatial ranges (300–600 m from the platform) or to the seasonal increase in site fidelity and residency. Sandy-bottom fish species (e.g., dab, grey gurnard) occurred only within the 500 m no-fishing zone, suggesting a potential benefit from reduced trawling and seabed disturbance (Van Elden et al., 2022). However, further observations are needed due to the lower sampling effort outside the fisheries exclusion area.

Total fish abundance was positively associated with the studied platform. The highest abundance values were observed within 10 m from the structure and decreased with increasing distance from the platform. Our study suggests that previous research, unable to sample as close to the structure as we did, likely underestimated fish abundance (Løkkeborg et al., 2002; Soldal et al., 2002). Gillnet assessments at two North Sea O&G platforms resulted in overall higher fish abundance (4-fold) at 0–55 m, 110–165 m, and 150–300 m than at greater distances (>600 m) (Løkkeborg et al., 2002). Contrastingly, no spatial patterns of fish densities were observed using trawl hauls and vessel-based hydroacoustics along distance gradients (50 to > 2000 m) from a Norwegian O&G platform (Soldal et al., 2002). Further, a distance gradient study at

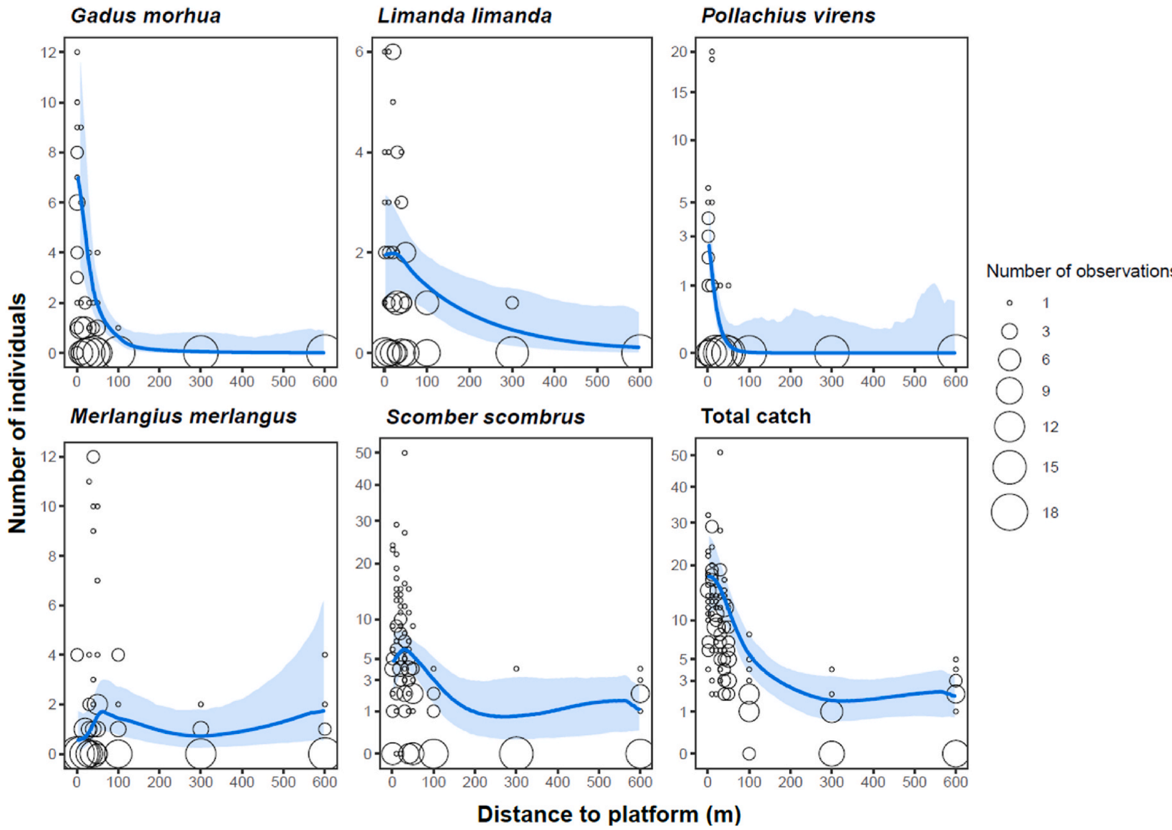

Fig. 5. Predicted fish abundance from the fitted spatial generalized additive mixed models (spatial GAMM) along the distance gradient from the studied platform for cod *Gadus morhua*, dab *Limanda limanda*, saithe *Pollachius virens*, whiting *Merlangius merlangus*, mackerel *Scomber scombrus*, and the total catch (all species). The distance estimations are derived from the spatial GAMM coordinates. The panels show predicted values (blue curve), 95% confidence intervals (light blue shade), observed values (circles), and the frequency of a particular observed value (circle size). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Parameters and output of the generalized additive mixed models of the association of fish body size (total length in cm) with the oil and gas (O&G) platform (distance to platform). An asterisk (*) represents statistical significance ($p < 0.05$).

Species	Goodness of fit, parametric coefficients	Smooth terms	Number of knots	Effective degrees of freedom	F-value	p-value
Gadus morhua (Atlantic cod)	Adjusted $R^2 = 0.22$; Deviance explained = 23%; REML = 508.7. Intercept: estimate = 39.8; standard error = 0.73; t-value = 54.5; p-value <0.01.	s(distance from a platform)	5	2.3	14.8	<0.01*
		s(time of the day)	24	0.03	0.002	0.33
Limanda limanda (Dab)	Adjusted $R^2 = 0.2$; Deviance explained = 24.6%; REML = 321.6. Intercept: estimate = 24.7; standard error = 0.5; t-value = 53.5; p-value <0.01.	s(distance from a platform)	7	3.2	4.2	<0.01*
		s(time of the day)	24	1.4	0.3	<0.05*
Pollachius virens (Saithe)	Adjusted $R^2 = 0.21$; Deviance explained = 27.6%; REML = 236.8. Intercept: estimate = 34.9; standard error = 1; t-value = 33.7; p-value <0.01.	s(distance from a platform)	5	3.6	2.38	<0.05*
		s(time of the day)	24	0.0003	0	0.65
Merlangius merlangus (Whiting)	Adjusted $R^2 = 0.17$; Deviance explained = 20.2%; REML = 368. Intercept: estimate = 26.9; standard error = 0.4; t-value = 67.5; p-value <0.01.	s(distance from a platform)	7	2.4	8.2	<0.01*
Scomber scombrus (Mackerel)	Adjusted $R^2 = 0.12$; Deviance explained = 12.9%; REML = 1773. Intercept: estimate = 33.2; standard error = 0.27; t-value = 121.7; p-value <0.01.	s(distance from a platform)	7	2.9	14.9	<0.01*
		s(time of the day)	24	3.5	1.6	<0.01*

an offshore wind farm in the Öresund Strait found no effect of the structure on spatial patterns of fish biodiversity and abundance at larger scales (130–1350 m), but increasing fish abundance would only be captured when implementing closer (20–140 m) sampling stations (Bergström et al., 2013). However, while the lack of sampling close to artificial structures may conceal fish assemblage patterns and underestimate abundance shifts, fish attraction could also change based on seasonality, habitat complexity, or structure location and age (Coolen et al., 2020; Reubens et al., 2013b). Importantly, changes in fish aggregation patterns at offshore O&G platforms and wind farms seem to be species-specific (Fujii, 2015; Reubens et al., 2013b).

The positive associations between fish abundance and O&G platform proximity were species-specific and mainly observed for cod, dab, and mackerel. Saithe only occurred within 50 m of the platform, but the analyses could not support a statistically significant spatial trend. Our results suggested that fish abundance changes occur over smaller distance ranges than reported in previous studies at O&G platforms in the North Sea, particularly for gadoids (e.g., cod, saithe) and flatfish (e.g., dab; Fujii, 2015; Ibanez-Erquiaga et al., 2024). For instance, while previous research reported cod and saithe abundance sharp declines

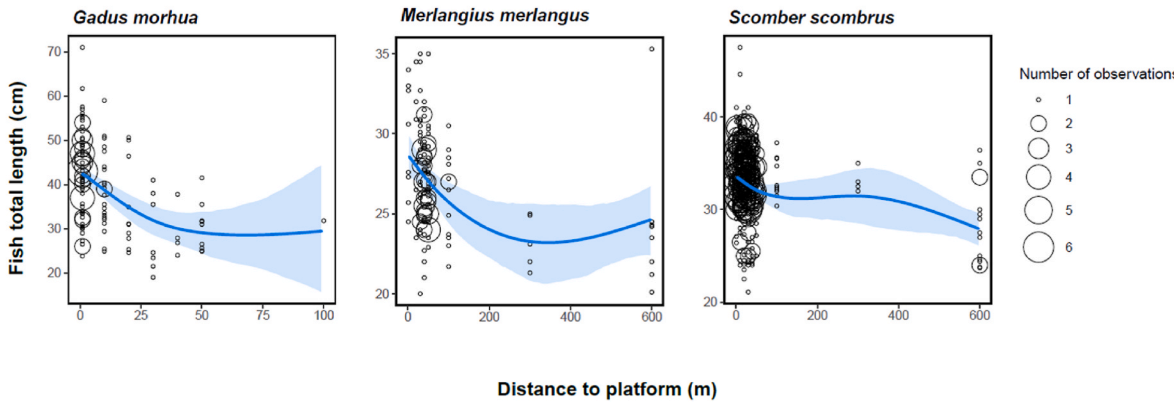

Fig. 6. Predicted fish body size (total length in cm) from the fitted generalized additive mixed models (distance GAMMs) along the distance gradient from the studied platform for cod *Gadus morhua*, whiting *Merlangius merlangus*, and mackerel *Scomber scombrus*. The panels show predicted values (blue curve), 95% confidence intervals (light blue shade), observed values (circles), and the frequency of a particular observed value (circle size). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

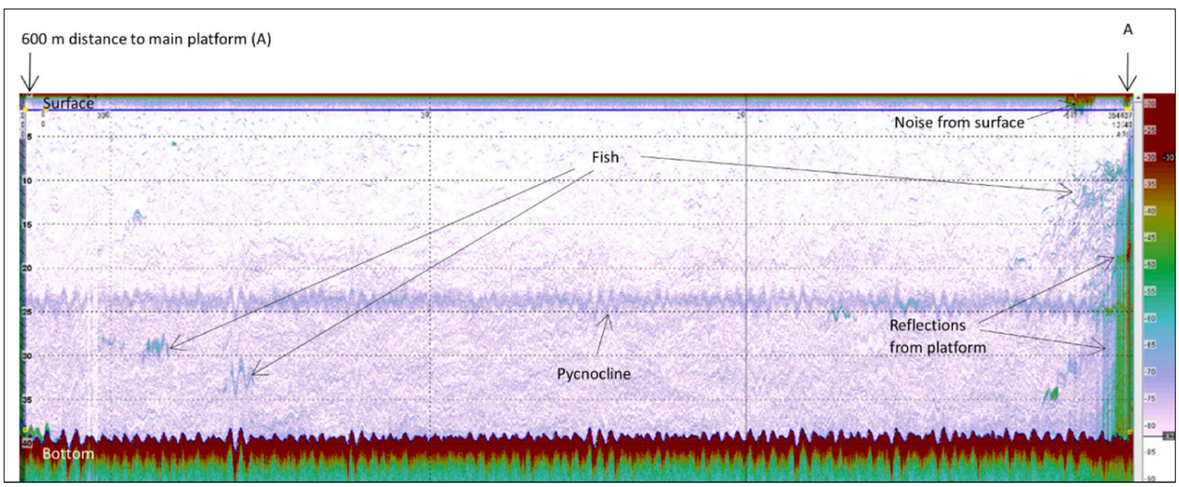

Fig. 7. Echogram displaying the backscattering strength (Sv; dB re 1 m^{-1}) from surface to bottom (40 m depth) along a straight line from 600 m distance to the platform (A). The color gradient represents backscatter (target strength) variation from highest (red) to lowest (white). The high backscatter from the seabed appears in red at the bottom. Single fish targets appear green. Purple single targets are weaker targets, such as fish with no swim bladder, jellyfish, or large crustaceans. Reflection/noise from the platform appears within 30 m of the structure. The vertical oscillating shape of the acoustic backscatter was caused by waves moving the RIB boat operating the device. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

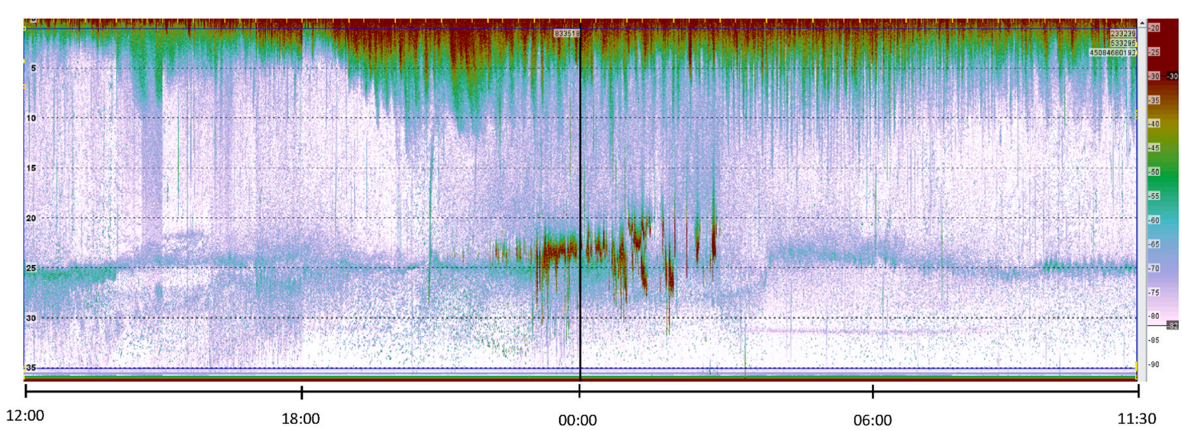

Fig. 8. Diel echogram displaying continuous ~24-h records (data were collected in 30-min intervals followed by 30-min breaks) by the WBAT during 23–24 July 2023 at 0 m distance to the platform. The vertical black line in the middle indicates data collected before and after midnight (local time).

beyond 100 m from platforms and whiting abundance decreases over 5000 m (Ibanez-Erquiaga et al., 2024), we found steeper declines within 50 m for cod, dab, and saithe. The observed spatial patterns suggest that these species may be using the platform as a feeding ground. For example, cod and plaice reportedly migrate in summer to feeding grounds where they feed opportunistically and exhibit reduced foraging movements (Buyse et al., 2023; Reubens et al., 2013b). The catch rates of saithe, only caught within 50 m of the structure, was nearly double in our study compared to local International Bottom Trawl Survey (IBTS; ICES, 2012) stations on open and soft bottom seabed. This may result from the aggregation of saithe near structures, but differences in catch efficiency between the two sampling methods cannot be excluded. However, a similar difference in catch rates was found for a Norwegian O&G platform (Fujii, 2015). Cod may shoal at offshore platforms (Todd et al., 2018), and has been recorded behind or under pipelines, potentially as an energy-saving strategy using current shadows generated by structures (Redford et al., 2021). Further, experimental measurements of metabolic rate in juvenile cod indicated that individuals in stone reef habitats may save energy in comparison with fish in sand bottom habitats (Schwartzbach et al., 2020). The increased heterogeneity of the habitat may influence the abundance of cod locally, in combination with additional factors such as prey availability and inter-specific interaction (Løkkeborg et al., 2002). Flatfish species (e.g., dab, plaice) reportedly exhibit avoidance behavior near offshore structures with increasing abundances shown away from the hard substrate (Todd et al., 2018; Van Hal et al., 2017). However, increases in flatfish abundance have been observed following the installation of O&G structures (Todd et al., 2020), and near wind turbines (Buyse et al., 2022). Flatfish are opportunistic feeders and may be attracted to artificial structures due to increased food provisioning, as tracking studies suggest that they approach hard substrates at offshore wind farms to forage (Buyse et al., 2023; Hinz et al., 2005). Food provisioning at artificial structures can be driven by benthic biomass production (Van Hal et al., 2017), but the physical presence of the structures may also affect the availability of zooplankton (Fujii and Jamieson, 2016). The mackerel aggregations observed within 50 m of the platform may suggest increased zooplankton availability, but further sampling is needed to assess temporal variability and temperature influence (Soldal et al., 2002; Fujii, 2016). Species-specific fish abundance trends along distance gradients may be influenced by different reef affinities among studied species, with steeper declines in the abundance of reef-dependent species (Dos Santos et al., 2010). Substrate dependency may explain the steeper declines in abundance for cod and saithe compared to dab, a flatfish with an affinity for sandy bottom.

Fish body size overall increased towards the platform for cod, whiting, and mackerel. Importantly, cod individuals caught at 1 m from the platform were on average > 10 cm larger than at 50 m. To our knowledge, this is the greatest size variation reported for cod near O&G platforms in the North Sea, and one of the only studies to explore body size variation along distance gradients for the species. Larger cod occurred in trawl catches closer (50–100 m) to a Norwegian O&G platform than at farther distances (>2000 m) (Soldal et al., 2002). Further, linear declines in body size over distance from platforms (0–120 m) in the Danish North Sea were estimated for cod (Ibanez-Erquiaga et al., 2024). In our study, the changes occurred over a shorter range (0–50 m) from the platform, potentially influenced by differences in spatial scales, seasonality, and intra-specific behavioral patterns. Size-related distribution may result from competitive exclusion where larger fish exclude smaller fish from the preferred habitat, or due to ontogenetic changes in foraging behavior as suggested for flounder (Henderson et al., 2014). For example, saithe shows changes in size distributions between seasons and years, suggesting differential habitat use by age groups near offshore platforms (Fujii and Jamieson, 2016). Our sampling occurred during summer when cod reportedly remain closer to artificial structures and prey on high-quality food items (Gimpel et al., 2023; Reubens et al., 2013b). Thus, larger cod could be predominantly using the habitat at the platform, restricting younger, smaller individuals. Importantly, >50% of the cod in our study were above the minimum landing body size (35 cm; De Oliveira and Walker, 2021), and 19% above the length at which 50% reach maturity (50.5 cm; Harrald et al., 2010). Thus, in addition to shelter and food provisioning by offshore structures, larger and even sexually mature cod may occur as a result of the protection from fisheries at the no-fishing zones enforced at O&G platforms. Our data also suggested a positive association between the O&G platform and body size for whiting, in contrast with previous observations near the study site which could not support similar associations (Ibanez-Erquiaga et al., 2024). Inconsistent occurrence of a species along the study gradient undermined our assessments of spatial patterns of fish body sizes and limited the exploration of additional condition parameters (e.g., Fulton's K, hepatosomatic index). For instance, we only caught two dab beyond 100 m from the platform and three saithe beyond 10 m. Thus, our study could not support associations between the O&G platform and body size for dab and saithe, or provide insight into fish condition at the platform.

Our methodology combined angling and hydroacoustics surveys, seeking synergies from two different sampling tools. While our angling gear was tailored for demersal fish species, the hydroacoustic surveys could target a wider range of species. The acoustic data support that little or no fish were present during daytime at depths shallower than the pycnocline at 23 m. Also, our acoustic 24-h recordings showed higher biological activity in the water column at night, indicating either that the fish move out from the platform, move up from the bottom, or come from elsewhere. Further, angling data showed that time of the day was in some cases significantly associated with fish abundance (total catch, whiting, mackerel), and fish size (dab, mackerel), but sampling was limited to daytime. Diel vertical patterns have been reported for cod and saithe at artificial structures, influenced by foraging behavior and inter-specific interactions (Fujii, 2015; Soldal et al., 2002). Cod and saithe abundance seemingly follow diel patterns as higher numbers have been reported during day time (Soldal et al., 2002). To fully understand diel fish activity at the platforms, the acoustic data could be supplemented with scientific angling at night.

Our results suggested that angling allows for assessing spatial changes in fish assemblages at O&G platforms. Similarly, we observed that hydroacoustic techniques can also provide information on horizontal spatial patterns, and along vertical gradients. Angling is selective, usually targets a subset of species and sizes, and may only capture fish actively foraging (Gimpel et al., 2023). On the other hand, hydroacoustics surveys provide powerful estimations of fish densities and body size but are challenged by species identification and beam reflection from the structure at closer ranges as we also found in our study (Punzo et al., 2015; Soldal et al., 2002). In the Gulf of Mexico, a hydroacoustics study along distance gradients (0 m to >100 m) from O&G platforms reported larger individuals (higher acoustic target strength) at distances ranging from 50 to 75 m followed by 0–50 m, and smaller fish from >75 m (Egerton et al., 2021). The authors suggested that larger fish associated with the structure were undetected as the areas inside the structure could not be surveyed using hydroacoustics (Egerton et al., 2021). Although this may be true to some extent, we did find a clear increasing trend in the acoustic target strength when moving closer to the platform. Methodological concerns limit other monitoring tools such as gillnetting, trawling, eDNA, and visual assessments with baited cameras, remotely operated vehicles (ROV), and divers (Alexander et al., 2022; Fujii, 2015; Rasmuson et al., 2022). Monitoring using fishing nets is affected by mesh size-dependent selectivity and net avoidance (gillnetting, trawling) (Rasmuson et al., 2022). Likewise, assessing fish abundance and biomass using eDNA is challenging, and artifacts associated with pollution and food waste near O&G platforms have been reported (Alexander et al., 2022). Visual assessments are also prone to bias as fish may exhibit different behavior when exposed to bait, light, and noise from an ROV, or the presence of a diver (Alexander et al., 2022; Fujii, 2015). Further, visual methods are challenged by limitations in light at depth and visibility depending on water clarity (Alexander et al., 2022). Inherent advantages and disadvantages of monitoring methodologies require planning based on research questions and data requirements, habitat characteristics, target species, resource availability, and technical restrictions (Hammerl et al., 2024; Rasmuson et al., 2022).

We used scientific angling systematically to allow for collecting data on benthic fish assemblages as close as 1 m away from the platform with standardized fishing effort (20 min per sampling) along a distance gradient to capture fine-scale spatial patterns of fish assemblages out to 600 m. The spatial scale of this study is rarely achieved due to the complexities of sampling near offshore O&G platforms. Distance-based studies can inform about associations between fish and offshore structures, and gradient approaches further allow the exploration of areas of influence (Methratta, 2020). Our methodology allowed capturing changes in fish assemblages within the spatial scale but is limited to a snapshot and does not include temporal or seasonal variability. Therefore, the observations could change with time and season. In the North East Atlantic, adult cod reportedly appeared after the installation of O&G structures but were absent two years after structure removal (Gates et al., 2019). The age of the structures becomes particularly relevant for the assessment of fish assemblages at newly installed structures, as the habitat will go through colonization processes and changing dynamics before reaching an equilibrium (Fowler et al., 2019; Reubens et al., 2014; Todd et al., 2021). In the North Sea, the abundance of cod reportedly increases seasonally in areas populated by artificial structures, such as O&G platforms (Wright et al., 2020). Additional considerations include structural characteristics and the environmental context as they may affect fish patterns within the study area (Fortune et al., 2024). A hydroacoustics assessment in the northeastern Gulf of Mexico found the area of influence of two decommissioned O&G platforms to be 104 m and 108 m and suggested a potential influence of the size of the platforms (White et al., 2022). Our study was limited to one platform and therefore our observations should be taken within the context of potential site-specific effects. At an artificial reef in Australia, no patterns of fish abundance occurred along a distance gradient (30–500 m), potentially influenced by the presence of natural reefs in the area (Scott et al., 2015). Similarly, *Lutjanus campechanus* in the Gulf of Mexico seemingly opts for natural reef habitats over local offshore structures (Osowski and Szedlmayer, 2022). In the present study, the platform was surrounded by homogeneous soft seabed, which may increase the fish-attraction effect of the platform. Finally, fisheries exclusion policies at offshore structures may influence fish assemblages. The 500 m no-fishing zone of the platform likely contributes to the higher fish biodiversity, abundance, and body sizes. In Australia, the fishing ban seems to have protected fish species targeted by commercial and recreational fisheries, as the fish occurred mostly around the O&G platform instead of their regular reef habitat in the area (Van Elden et al., 2022). Here we observed commercially important species (e.g., cod, saithe) well represented near the platform that would otherwise be targeted by fishing vessels in open areas. Finally, our study was spatially constrained, primarily covering the southern and eastern areas from the platform, leading to an uneven distribution of sampling stations across directions. We sought to account for the directionality variability by using spatial terms (latitude, longitude) in the models, which captured changes in community composition (e.g., species richness, abundance). However, uncertainty associated with, for example, the closest structure type, or current directions, may have been overlooked.

This study provides a snapshot of the potential role of offshore O&G platforms as habitats of interest for fish communities in the North Sea. Our results expand the knowledge available for debating the ecological implications of complete structure removal through decommissioning. However, research into the local effects of the platforms on fish fitness, survival, production, and dispersal (eggs and larvae) is needed to inform management action. Decommissioning decisions are framed primarily within local policies and include stakeholder interests, financial impacts, and technical limitations, among other factors (Vidal et al., 2022). In the North Sea, decommissioning policies require the complete removal of disused installations (OSPAR Commission, 1998). Complete platform removal has traditionally been considered to achieve the best ecological outcome, however, alternative decommissioning options may have better contributions towards environmental targets (Knights et al., 2024; Ounanian et al., 2020). For example, policies could allow for platform repurposing as artificial reefs, as implemented in the Gulf of Mexico and California through the "Rigs-to-Reefs" program (Knights et al., 2024). Shifting from a paradigm of environmental protection to one of restoration may further benefit the ecosystem (Ounanian et al., 2020). Policy debate on decommissioning plans for O&G platforms needs to integrate the expansion and eventual decommissioning of other offshore structures such as wind farms. Contemplating decommissioning alternatives from an ecological perspective calls for exploring the losses and gains from platform removal, which must be built on knowledge of the ecological role of offshore structures.

CRediT authorship contribution statement

Bruno Ibanez-Erquiaga: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Henrik Baktoft:** Visualization, Validation, Methodology. **Tobias K. Mildenberger:** Visualization, Validation, Methodology, Formal analysis. **Jonas Teilmann:** Writing – original draft, Visualization, Methodology, Funding acquisition. **Lars Kleivane:** Writing – review & editing, Methodology, Investigation. **Leandra M. Kornau:** Writing – review & editing, Investigation. **Mette D. Agersted:** Writing – original draft, Investigation, Formal analysis. **Sixten M. Hüllert:** Writing – review & editing, Investigation. **Jon C. Svendsen:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We kindly acknowledge the Danish Underground Consortium (TotalEnergies, Noreco & Nordsøfonden) for granting permission to publish the data included in this study. We also thank the Danish Offshore Technology Centre (DTU Offshore) for its support. Thanks to Fairpoint Outdoors for aiding with field equipment. This study has been funded by DTU Offshore under the ABN program and by the Dansk Center for Havforskning (DCH). The funding sources had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2025.106959.

Data availability

Data will be made available on request.

References

Alexander, J.B., Marnane, M.J., Elsdon, T.S., Bunce, M., Songploy, S., Sitaworawet, P., Harvey, E.S., 2022. Complementary molecular and visual sampling of fish on oil and gas platforms provides superior biodiversity characterisation. Mar. Environ. Res. 179, 105692.

Ballerstedt, S., 2008. *Trisopterus luscus* bib or pouting. In: Tyler-Walters, H., Hiscock, K. (Eds.), *Marine Life Information Network: Biology And Sensitivity Key Information Reviews*. Plymouth: Marine Biological Association of the United Kingdom. Available from: https://www.marlin.ac.uk/species/detail/1876. (Accessed 21 March 2024).

Berges, B.J.P., Knaap, I.V.D., Van Keeken, O.A., Reubens, J., Winter, H.V., 2024. Strong site fidelity, residency and local behaviour of Atlantic cod (*Gadus morhua*) at two types of artificial reefs in an offshore wind farm. R. Soc. Open Sci. 11 (7), 240339.

Bergström, L., Sundqvist, F., Bergström, U., 2013. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. Mar. Ecol. Prog. Ser. 485, 199–210.

Bilous, M., McNicholl, D.G., Dunmall, K.M., 2022. Coastal marine biodiversity in the western Canadian Arctic. Arctic Science 8 (4), 1127–1147.

Bond, T., Partridge, J.C., Taylor, M.D., Cooper, T.F., McLean, D.L., 2018. The influence of depth and a subsea pipeline on fish assemblages and commercially fished species. PLoS One 13 (11), e0207703.

Bull, A.S., Love, M.S., 2019. Worldwide oil and gas platform decommissioning: a review of practices and reefing options. Ocean Coast Manag. 168, 274–306.

Buyse, J., Hostens, K., Degraer, S., De Backer, A., 2022. Offshore wind farms affect the spatial distribution pattern of plaice *Pleuronectes platessa* at both the turbine and wind farm scale. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 79 (6), 1777–1786.

Buyse, J., Reubens, J., Hostens, K., Degraer, S., Goossens, J., De Backer, A., 2023. European plaice movements show evidence of high residency, site fidelity, and feeding around hard substrates within an offshore wind farm. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. fsad179.

Claisse, J.T., Love, M.S., Meyer-Gutbrod, E.L., Williams, C.M., Pondella, D.J., Daniel, J., 2019. Fishes with high reproductive output potential on California offshore oil and gas platforms. Bull. Mar. Sci. 95 (4), 515–534.

Claisse, J.T., Pondella, D.J., Love, M., Zahn, L.A., Williams, C.M., Bull, A.S., 2015. Impacts from partial removal of decommissioned oil and gas platforms on fish biomass and production on the remaining platform structure and surrounding shell mounds. PLoS One 10 (9), e0135812.

Colwell, R.K., 2009. Biodiversity: concepts, patterns, and measurement. The Princeton guide to ecology 663, 257–263.

Coolen, J.W., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W., Faasse, M.A., et al., 2020. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 1250–1265.

De Oliveira, J., Walker, N., 2021. Stock Annex: Cod (Gadus morhua) in Subarea 4 and Divisions 7. D and 20 (North Sea, Eastern English Channel, Skagerrak). ICES Stock Annex.

Didderen, K., Lengkeek, W., Bergsma, J.H., van Dongen, U., Driessen, F.M.F., Kamermans, P., 2020. *WWF & ARK Borkum Reef Ground Oyster Pilot: Active Restoration of Native Oysters in the North Sea-Monitoring September 2019* (No. 19-227). Bureau Waardenburg.

Dos Santos, L.N., Brotto, D.S., Zalmon, I.R., 2010. Fish responses to increasing distance from artificial reefs on the Southeastern Brazilian Coast. J. Exp. Mar. Biol. Ecol. 386 (1–2), 54–60.

Egerton, J.P., Bolser, D.G., Grüss, A., Erisman, B.E., 2021. Understanding patterns of fish backscatter, size and density around petroleum platforms of the US Gulf of Mexico using hydroacoustic data. Fish. Res. 233, 105752.

EMODnet, 2024. https://emodnet.ec.europa.eu/en/seabed-habitats. (Accessed 21 March 2024).

Fortune, I.S., Paterson, D.M., 2020. Ecological best practice in decommissioning: a review of scientific research. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 1079–1091.

Fortune, I.S., Madgett, A.S., Scarborough Bull, A., Hicks, N., Love, M.S., Paterson, D.M., 2024. Haven or hell? A perspective on the ecology of offshore oil and gas platforms. PLOS Sustainability and Transformation 3 (4), e0000104.

Fowler, A.M., Jørgensen, A.M., Coolen, J.W., Jones, D.O., Svendsen, J.C., Brabant, R., Rumes, B., Degraer, S., 2019. The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 1109–1126.

Fowler, A.M., Macreadie, P.I., Jones, D.O.B., Booth, D.J., 2014. A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. Ocean Coast Manag. 87, 20–29.

Friedlander, A.M., Ballesteros, E., Fay, M., Sala, E., 2014. Marine communities on oil platforms in Gabon, West Africa: high biodiversity oases in a low biodiversity environment. PLoS One 9 (8), e103709.

Froese, R., Pauly, D., 2024. FishBase. Available from: https://www.fishbase.se/search.php. (Accessed 21 March 2024).

Fujii, T., 2015. Temporal variation in environmental conditions and the structure of fish assemblages around an offshore oil platform in the North Sea. Mar. Environ. Res. 108, 69–82.

Fujii, T., 2016. Potential influence of offshore oil and gas platforms on the feeding ecology of fish assemblages in the North Sea. Mar. Ecol. Prog. Ser. 542, 167–186.

Fujii, T., Jamieson, A.J., 2016. 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. 126, 481–487.

Gates, A.R., Horton, T., Serpell-Stevens, A., Chandler, C., Grange, L.J., Robert, K., et al., 2019. Ecological role of an offshore industry artificial structure. Front. Mar. Sci. 6, 675.

Gimpel, A., Werner, K.M., Bockelmann, F.D., Haslob, H., Kloppmann, M., Schaber, M., Stelzenmüller, V., 2023. Ecological effects of offshore wind farms on Atlantic cod (*Gadus morhua*) in the southern North Sea. Sci. Total Environ. 878, 162902.

Glenn, H.D., Cowan Jr, J.H., Powers, J.E., 2017. A comparison of red snapper reproductive potential in the northwestern Gulf of Mexico: natural versus artificial habitats. Marine and Coastal Fisheries 9 (1), 139–148.

Hammerl, C., Möllmann, C., Oesterwind, D., 2024. Identifying fit-for purpose methods for monitoring fish communities. Front. Mar. Sci.

Harrald, M., Wright, P.J., Neat, F.C., 2010. Substock variation in reproductive traits in North Sea cod (*Gadus morhua*). Can. J. Fish. Aquat. Sci. 67 (5), 866–876.

Harvey, E.S., Watts, S.L., Saunders, B.J., Driessen, D., Fullwood, L.A., Bunce, M., et al., 2021. Fish assemblages associated with oil and gas platforms in the Gulf of Thailand. Front. Mar. Sci. 8, 664014.

Henderson, M.J., Fabrizio, M.C., Lucy, J.A., 2014. Movement patterns of summer flounder near an artificial reef: effects of fish size and environmental cues. Fish. Res. 153, 1–8.

Hinz, H., Kröncke, I., Ehrich, S., 2005. The feeding strategy of dab Limanda limanda in the southern North Sea: linking stomach contents to prey availability in the environment. J. Fish. Biol. 67, 125–145.

Ibanez-Erquiaga, B., Baktoft, H., Wilms, T., Mildenberger, T.K., Svendsen, J.C., 2024. Fish aggregations at oil and gas platform foundations in the North Sea. Fish. Manag. Ecol., e12693

ICES, 2012. Manual for the international bottom trawl surveys. Series of ICES Survey Protocols. *SISP 1-IBTS IV*.

ICES, 2022. Working group on the assessment of demersal stocks in the North Sea and skagerrak (WGNSSK). ICES Scientific Reports 4, 1367.

Knights, A.M., Lemasson, A.J., Firth, L.B., Beaumont, N., Birchenough, S., Claisse, J., et al., 2024. To what extent can decommissioning options for marine artificial structures move us toward environmental targets? J. Environ. Manag. 350, 119644.

Korneliussen, R.J., Ona, E., Eliassen, I., Heggelund, Y., Patel, R., Godø, O.R., et al., 2006. The large scale survey system-LSSS. Proceedings of the 29th Scandinavian Symposium on Physical Acoustics 29, 2006. Ustaoset.

Lawrence, J.M., Fernandes, P.G., 2022. A typology of North Sea oil and gas platforms. Sci. Rep. 12 (1), 8079.

Lawrence, J.M., Speirs, D.C., Heath, M.R., Fujii, T., Burns, F., Fernandes, P.G., 2024. Elevated fish densities extend kilometres from oil and gas platforms. PLoS One 19 (5), e0302738.

Løkkeborg, S., Humborstad, O.B., Jørgensen, T., Soldal, A.V., 2002. Spatio-temporal variations in gillnet catch rates in the vicinity of North Sea oil platforms. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 59 (Suppl. l), S294–S299.

Marnane, M.J., Schramm, K.D., Driessen, D., Fullwood, L.A., Saunders, B.J., Songploy, S., et al., 2022. Evidence of fish following towed oil and gas platforms to a reefing site and rapid colonisation. Mar. Environ. Res. 180, 105728.

Martins, M.C.I., Carter, M.I., Rouse, S., Russell, D.J., 2023. Offshore energy structures in the North Sea: past, present and future. Mar. Pol. 152, 105629.

McLean, D., Speed, C.W., Birt, M.J., Colquhoun, J., Case, M., Stowar, M., et al., 2022. Habitat value of subsea wells and pipelines for fishery target species in Australia. Front. Mar. Sci. 9, 960496.

Methratta, E.T., 2020. Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 890–900.

Meyer-Gutbrod, E.L., Love, M.S., Schroeder, D.M., Claisse, J.T., Kui, L., Miller, R.J., 2020. Forecasting the legacy of offshore oil and gas platforms on fish community structure and productivity. Ecol. Appl. 30 (8), e02185.

NOAA - National Oceanic And Atmospheric Administration, U.S. Department Of Commerce, 2024. NOAA fisheries species directory. Available from: https://www.fisheries.noaa.gov/species-directory. (Accessed 21 March 2024).

Oksanen, J., 2010. Vegan: community ecology package. http://vegan.r-forge.r-project.org/.

Ona, E., 1999. Methodology for target strength measurements. ICES Coop. Res. Rep. 235, 59.

Osowski, A.R., Szedlmayer, S.T., 2022. Red snapper (*Lutjanus campechanus*) abundance on oil and gas platforms based on mark–recapture methods in the northern Gulf of Mexico. Can. J. Fish. Aquat. Sci. 79 (9), 1546–1560.

OSPAR Commission, 1998. Decision 98/3 on the disposal of disused offshore installations. In: Ministerial Meeting of the OSPAR Commission. London, UK.

Ounanian, K., van Tatenhove, J.P., Ramírez-Monsalve, P., 2020. Midnight at the oasis: does restoration change the rigs-to-reefs debate in the North Sea? J. Environ. Pol. Plann. 22 (2), 211–225.

Pielou, E.C., 1966. The measurement of diversity in different types of biological collections. J. Theor. Biol. 13, 131–144.

Punzo, E., Malaspina, S., Domenichetti, F., Polidori, P., Scarcella, G., Fabi, G., 2015. Fish detection around offshore artificial structures: preliminary results from hydroacoustics and fishing surveys. J. Appl. Ichthyol. 31, 48–59.

R Development Core Team, 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rasmuson, L.K., Fields, S.A., Blume, M.T., Lawrence, K.A., Rankin, P.S., 2022. Combined video–hydroacoustic survey of nearshore semi-pelagic rockfish in untrawlable habitats. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 79 (1), 100–116.

Redford, M., Rouse, S., Hayes, P., Wilding, T.A., 2021. Benthic and fish interactions with pipeline protective structures in the North Sea. Front. Mar. Sci. 8, 652630.

Reubens, J.T., Degraer, S., Vincx, M., 2014. The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. Hydrobiologia 727, 121–136.

Reubens, J.T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S., Vincx, M., 2013a. Aggregation at windmill artificial reefs: CPUE of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea. Fish. Res. 139, 28–34.

Reubens, J.T., Pasotti, F., Degraer, S., Vincx, M., 2013b. Residency, site fidelity and habitat use of Atlantic cod (Gadus morhua) at an offshore wind farm using acoustic telemetry. Mar. Environ. Res. 90, 128–135.

RStudio Team, 2024. RStudio. Integrated development for R [Computer software]. Boston, MA: RStudio.

Schwartzbach, A., Behrens, J.W., Svendsen, J.C., 2020. Atlantic cod *Gadus morhua* save energy on stone reefs: implications for the attraction versus production debate in relation to reefs. Mar. Ecol. Prog. Ser. 635, 81–87.
Scott, M.E., Smith, J.A., Lowry, M.B., Taylor, M.D., Suthers, I.M., 2015. The influence of an offshore artificial reef on the abundance of fish in the surrounding pelagic environment. Mar. Freshw. Res. 66 (5), 429–437.
Shannon, C.E., 1948. A mathematical theory of communication. The Bell system technical journal 27 (3), 379–423.
Sih, T.L., Cure, K., Yilmaz, I.N., McLean, D., Macreadie, P.I., 2022. Marine life and fisheries around offshore oil and gas structures in southeastern Australia and possible consequences for decommissioning. Front. Mar. Sci. 9, 979212.
Snodgrass, D.J., Orbesen, E.S., Walter, J.F., Hoolihan, J.P., Brown, C.A., 2020. Potential impacts of oil production platforms and their function as fish aggregating devices on the biology of highly migratory fish species. Rev. Fish Biol. Fish. 30, 405–422.
Soldal, A.V., Svellingen, I., Jørgensen, T., Løkkeborg, S., 2002. Rigs-to-reefs in the North Sea: hydroacoustic quantification of fish in the vicinity of a "semi-cold" platform. ICES J. Mar. Sci. 59 (Suppl. l), S281–S287.
Sommer, B., Fowler, A.M., Macreadie, P.I., Palandro, D.A., Aziz, A.C., Booth, D.J., 2019. Decommissioning of offshore oil and gas structures–Environmental opportunities and challenges. Sci. Total Environ. 658, 973–981.
Stenberg, C., Støttrup, J., Dahl, K., Lundsteen, S., Göke, C., Andersen, O.N., 2015. Ecological benefits from restoring a marine cavernous boulder reef in Kattegat, Denmark. National Institute of Aquatic Resources. Danmarks Tekniske Universitet.
Støttrup, J.G., Dahl, K., Niemann, S., Stenberg, C., Reker, J., Stamphøj, E.M., et al., 2017. Restoration of a boulder reef in temperate waters: strategy, methodology and lessons learnt. Ecol. Eng. 102, 468–482.
Tassetti, A.N., Minelli, A., Ferrà, C., Guicciardi, S., Gaetani, A., Fabi, G., 2020. An integrated approach to assess fish spatial pattern around offshore gas platforms: a pilot study in the Adriatic Sea. Mar. Environ. Res. 162, 105100.
Todd, V.L., Lavallin, E.W., Macreadie, P.I., 2018. Quantitative analysis of fish and invertebrate assemblage dynamics in association with a North Sea oil and gas installation complex. Mar. Environ. Res. 142, 69–79.
Todd, V.L., Susini, I., Williamson, L.D., Todd, I.B., McLean, D.L., Macreadie, P.I., 2021. Characterizing the second wave of fish and invertebrate colonization of an offshore petroleum platform. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 78 (3), 1131–1145.
Todd, V.L., Williamson, L.D., Cox, S.E., Todd, I.B., Macreadie, P.I., 2020. Characterizing the first wave of fish and invertebrate colonization on a new offshore petroleum platform. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 1127–1136.
Tothill, T., Meeuwig, J.J., Van Elden, S., 2024. The vertical distribution of fish on two offshore oil platforms. Front. Mar. Sci. 11, 1328672.
Vandeperre, F., Parra, H., Pham, C.K., Machete, M., Santos, M., Bjorndal, K.A., Bolten, A. B., 2019. Relative abundance of oceanic juvenile loggerhead sea turtles in relation to nest production at source rookeries: implications for recruitment dynamics. Sci. Rep. 9 (1), 13019.
Van Elden, S., Meeuwig, J.J., Hobbs, R.J., 2022. Offshore platforms as novel ecosystems: a case study from Australia's Northwest Shelf. Ecol. Evol. 12 (2), e8496.
Van Hal, R., Griffioen, A.B., Van Keeken, O.A., 2017. Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm. Mar. Environ. Res. 126, 26–36.
Vidal, P.D.C.J., González, M.O.A., de Vasconcelos, R.M., de Melo, D.C., de Oliveira Ferreira, P., Sampaio, P.G.V., da Silva, D.R., 2022. Decommissioning of offshore oil and gas platforms: a systematic literature review of factors involved in the process. Ocean Eng. 255, 111428.
Watson, S.M., McLean, D.L., Balcom, B.J., Birchenough, S.N., Brand, A.M., Camprasse, E. C., et al., 2023. Offshore decommissioning horizon scan: research priorities to support decision-making activities for oil and gas infrastructure. Sci. Total Environ. 878, 163015.
White, A.L., Patterson III, W.F., Boswell, K.M., 2022. Distribution of acoustic fish backscatter associated with natural and artificial reefs in the Northeastern Gulf of Mexico. Fish. Res. 248, 106199.
Wilber, D.H., Carey, D.A., Griffin, M., 2018. Flatfish habitat use near North America's first offshore wind farm. J. Sea Res. 139, 24–32.
Wood, S.N., 2017. Generalized Additive Models: an Introduction with R, second ed. Chapman and Hall/CRC.
Wright, S.R., Lynam, C.P., Righton, D.A., Metcalfe, J., Hunter, E., Riley, A., Garcia, L., Posen, P., Hyder, K., 2020. Structure in a sea of sand: fish abundance in relation to man-made structures in the North Sea. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77 (3), 1206–1218.
Zuur, A.F., Ieno, E.N., 2016. A protocol for conducting and presenting results of regression-type analyses. Methods Ecol. Evol. 7 (6), 636–645.