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Ecological recovery of benthic fauna from contamination near oil and gas platforms

Christopher P. Lynam [a,*], Clement Garcia [a], Zelin Chen [b], Gareth E. Thomas [b,c], Natalie Hicks [b], Stefan G. Bolam [a], Debbie J.F. Russell [d]

[a] Centre for Environment, Fisheries and Aquaculture Science, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK
[b] School of Life Sciences, University of Essex, Colchester, Essex CO4 3SQ, UK
[c] Department of Life Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK
[d] School of Biology, University of St Andrews, East Sands, Fife KY16 8LB, UK

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ABSTRACT

Many oil and gas platforms in the North Sea are nearing their end of life and there is an urgent need to understand the legacy effects of associated seabed contamination on benthic communities. We use data from industry-based monitoring surveys, 1985–2015, in a North Sea wide study to investigate change in contaminants and the biomass of benthic functional groups (small infauna, small mobile epifauna, infaunal macrobenthos, and epifaunal macrobenthos). Total hydrocarbon concentrations in sediment samples exceeded 150,000 μg/g between 1992 and 1998 and within 250 m of 6 different platforms. Statistical relationships between chemical concentration, distance from platform and year were modelled using Generalized Additive Mixed Models for 5 environmentally distinct clusters of 236 platforms. Non-linear decreases were identified for total hydrocarbon concentrations as distance from platforms increased for four clusters, but not the deep-water cluster to the north of Scotland. Similarly structured statistical models with benthic biomass as the response variable and total hydrocarbon concentration as the predictor showed that relationships between them varied among clusters and functional groups. Following management measures to reduce contaminant concentrations, the biomass of benthic groups has since returned to reference conditions across many sites. Our results provide a functional perspective that can support ecosystem modelling, inform environmental assessments and support the implementation of management measures.

1. Introduction

Oil and gas platforms, and their associated infrastructures, impact seabed habitats during construction, but the extent to which their presence disrupts the biomass of benthic communities both in and on the sediment (i.e. infauna and epifauna) is not well documented. Impacts on the seabed associated with this sector vary widely. In addition to the initial physical impacts related to construction, exploratory drilling, subsequent construction, operation and decommissioning of platforms, all have the potential to impact marine ecosystems due to spillage and dispersal of contaminated fluids into both the water column and nearby sediments (Bakke et al., 2013; Ball et al., 2012; National Research Council, 2003). Bakke et al. (2013) reported that, prior to the introduction of contaminant regulations in 1993/1996, heavily contaminated oil-based rock cuttings from drilling piled up on the seabed around platforms causing widespread contamination of sediments (out to 5–10 km) with changes in benthic macrofauna detectable up to 5 km in terms of abundance and diversity. However, following the implementation of regulations on discharges of oil-based muds and contaminated cuttings during the 1990s by the Paris Commission (PARCOM Decision 92/2), disturbance of fauna by oil-contaminated cuttings was typically restricted to within 500 m of platforms (Bakke et al., 2013). Bakke et al. (2013) report that 25,000 tons of oil was discharged to the North Sea with cuttings in 1985, which decreased to 13,000 tons in 1990. Hydrocarbons, however, were also discharged in cuttings materials through the use of organic-phase fluids, until discharges were prohibited in 2001 (with the exception of cuttings with low levels of contamination i.e. concentrations of ≤1 % by weight) with

* Corresponding author at: International Council for the Exploration of the Sea, H. C. Andersens Boulevard 44-46, DK 1553 Copenhagen V, Denmark.
E-mail addresses: chris.lynam@ices.dk (C.P. Lynam), clement.garcia@cefas.gov.uk (C. Garcia), zelin.chen@essex.ac.uk (Z. Chen), gareth.thomas@nhm.ac.uk (G.E. Thomas), natalie.hicks@essex.ac.uk (N. Hicks), stefan.bolam@cefas.gov.uk (S.G. Bolam), dr60@st-andrews.ac.uk (D.J.F. Russell).

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the adoption of OSPAR Decision 2000/3 (OSPAR Commission, 2000). Impacts on the benthos can however continue several years after discharge of contaminants (Olsgard and Gray, 1995; Henry et al., 2017) due to their persistence in sediments in surrounding areas prior to the degradation of toxins (Mair et al., 1987). In a recent post-decommisioning study, Marappan et al. (2022) reported that macrobenthic communities in 2003 remained highly modified up to 500 m away from the Hutton Tension Leg Platform in the North Sea and this was attributed to hydrocarbon pollution following contamination by a range of drilling fluids.

More recently, traditional drilling fluids have been replaced with a range of water-based fluids, low-toxicity oil-based muds and synthetic-based drilling muds (Neff, 2005). Although modern drilling fluids are not without potential for impact on benthic species (Bakke et al., 2013), likely via physical disturbance (smothering and/or burial of sessile species), there is no evidence of bioaccumulation or toxicity (Neff, 2005). While these effects from contamination impact and on biodiversity and distribution are well documented, the impact of the platforms on infaunal and epifaunal biomass has been given much less attention. For effective management, policy makers and planners require robust information regarding both the direct effects (such as habitat loss or smothering) and indirect effects on the wider food web. However, reliable, empirical data regarding the latter is presently lacking.

Studies on the impacts of oil and gas platforms on infaunal assemblages have yielded variable and often conflicting outcomes, inferring that indirect impacts are likely to be principally governed by site-specific characteristics. Gillett et al. (2020), for example, examined benthic infauna from 20 sites around four oil platforms in the Santa Barbara Channel (California). In this study, with minimal levels of exposure to contaminants from the platforms between 250 m and 1 km from platforms, they found infaunal assemblages to be similar to those sampled between 1 and 2 km. From a study of four different platforms (Gorm, Tyra E, Dan F, South Arne) in the eastern North Sea, Marappan et al. (2022) observed a reduced biodiversity <100 m of the Dan F platform, and elevated pollutant concentrations and reduced biodiversity 250 m from the South Arne platforms along with an increase in the presence of non-native species and reduced seabed integrity, but no impact was associated with the other platforms (i.e. Gorm, Tyra E). Given the contrasting findings of these studies which have all involved sampling at different distances from platforms, to objectively quantify impacts of platforms it is evident that is it important to sample as near to the platforms as practicable and to distinguish sites that are potentially impacted by chemical discharges from sites that are not, while accounting for differences in the local environmental conditions (including sediment type and hydrodynamics).

Recently, benthic data from industry sampling have been compiled by Oil and Gas UK for both infauna and epifauna sampled at platforms across the North Sea since 1975 (UKbenthos Database Version 5.18, Available at https://oeuk.org.uk/environment-resources/). This combined data repository facilitates the opportunity to explicitly analyse the impacts of platforms and their operation on the benthic environment. The first study to use these data investigated the impact of drill cuttings on indicator species (including the polychaetes *Capitella* spp., *Ophryotrocha* spp., and the bivalve *Thyasira* spp.) for 17 selected platforms across the North Sea (Henry et al., 2017). The study contrasted variation in abundance data relative to environmental gradients from the post-drilling period to variation in abundance data relative to environmental gradients in the reference period pre-drilling, and found impacts were limited to within 1.2 km of platforms in the northern and central North Sea, with no detectable impact in the southern North Sea. Henry et al. (2017) suggested that impacts could persist for up to 8 years, but the study does not provide information on how this impact might alter ecosystem functioning in terms of biomass of benthic functional groups. Chen et al. (2024), using data from nine platforms in the North Sea, found that diversity, abundance and biomass were depleted within 500 m of platforms for some trophic groups (i.e. filter-feeder, predator and detritivore groups) but not others (i.e. grazer, scavenger and parasite) and that chemical effects were limited to this spatial extent in both pre- and post-exploitation phases with higher values post-exploitation.

This study seeks to expand the evidence base on the impacts of oil and gas platforms (using data from 236 platforms) across the entire North Sea on the biomass of 4 benthic functional groups. We aggregate data from over 3000 distinct taxonomic groups, typically species level but also including groups at family level, (in the Oil and Gas UK database 'UKbenthos' version 5.18) into the benthic functional groups used in current models of the North Sea (Hill et al., 2021; ICES, 2016; Lynam et al., 2017; Mackinson et al., 2018; Püts et al., 2023), namely: small infauna, small mobile epifauna, infaunal macrobenthos, and epifaunal macrobenthos. These existing functional groups are primarily based on size and habitat (infauna versus epifauna) and they are part of an established body of work on food-web dynamics originating from the study of Mackinson and Daskalov (2007) that aimed to provide simple benthic functional groups of relevance to demersal fish predators. These functional groups differ from the trophic groups of Chen et al. (2024) that were based on functional traits of the benthic organisms, since the functional groups of Mackinson and Daskalov (2007) consider the availability of the benthic organisms as prey for higher trophic levels.

We use benthic data between 4 and 1500 m from oil and gas platforms that are associated with chemical sampling of hydrocarbons and metals, enabling our study to investigate how contamination changes with distance from platforms and how benthic biomass changes in relation to contamination. We expect that sediments nearer to platforms will show elevated levels of chemical contamination and a reduction in the biomass of benthic species relative to reference conditions as shown by Chen et al. (2024). Given the study of Bakke et al. (2013), we aim to identify if recovery of benthic biomass is evident across the North Sea following management intervention in the 1990s. Finally, our study will improve the evidence base supporting decisions on future consents and approval for new energy infrastructure projects (including renewables) and the decommissioning of existing platforms.

2. Methods

2.1. Oil and gas platform, chemical and fauna data preparation

The data for chemicals and biota were sourced from the UK Oil and Gas industry from the online database: The Offshore Oil & Gas U.K. Database of Offshore Environmental Survey (UKBenthos Version 5.18; Available at: https://oeuk.org.uk/publications-resources/). The UKBenthos database contains entries from >700 surveys between 1975 and 2015 and data were extracted for 236 man-platforms (Table S1). Benthic species data were retained for quantitative gears from which density estimates could be made, i.e. mini Hamon, Day and Van Veen grabs and box corers - data from trawls, scuba and dredge approaches were excluded. Specifically, survey metadata, environmental parameters and faunal information were extracted from the dataset. As part of the quality control step, the data were checked for consistent spelling and revised to accommodate taxonomic changes. Furthermore, empty records or those without metadata were removed. Data were retained from samples taken up to 1500 m from the platforms only to minimize the potential changes in environment along gradients within sample transects.

In this paper, we define the functional group of "epifauna" as the subset of epifauna that can be correctly sampled by grabs (Eleftheriou, 2013). Epifauna and infauna datasets are notoriously difficult to compare accurately, especially in the context of using multiple data sources from the industry. The traditional epifaunal gears (dredge and trawl) are not fully quantitative and tend to be biased towards larger, over-dispersed species (e.g. *Cancer* sp., *Asterias* sp., *Buccinum* sp.) and poorly sample the smaller epifaunal species (e.g. tube-worms, Ophiura) for which a grab or a corer is better. It was therefore preferred to limit the influence of gear-effects and to consider the part of the epifaunal communities that can be sampled by grabs. Because we acknowledge that same bias consistently across all stations we consider our results to be robust.

The faunal abundance values were standardized at sampling station level by taking an average of replicates where multiple existed (typically 3–5 replicates). As this study focuses on benthic invertebrates, data entries on fish, plants and pelagic species were removed. Data for species with names that had no match within WoRMS (https://www.marinespecies.org/) were removed, as were all records labelled "juvenile" to avoid possible noise due to recruitment events. Since the biological data contained abundance measurements only, data on average individual-body mass were used to derive species-level biomass estimates [g m^{-2}] for each sampling station. A full list of species included in the analysis is given in supplementary materials.

Hydrocarbon and metal concentrations were extracted from the UKBenthos database and matched to samples of benthic species by site. Data were retained for records of total hydrocarbon concentration (THC) in sediment as determined by gas chromatography, normal alkane concentration (*n*-alkanes), high molecular-weight (mw) polycyclic aromatic hydrocarbons (PAHs with four of more aromatic rings and with mw of 202, 228, 252 and 276) and low molecular-weight (mw) polycyclic aromatic hydrocarbons (naphthalenes, mw 128), phenanthrenes (mw 178) and diabenzothiophenes (mw 184) from ultrasonication were retained along with Barium, (Ba), Cadmium (Cd), Chromium (Cr), Iron (Fe), Nickel (Ni), Lead (Pb), Vanadium (VA) and Zinc (Zn). From the selected hydrocarbon dataset (1759 records), THC in sediment, determined by gas chromatography, was most frequently reported (72 % of records from 199 platforms). For other aromatic hydrocarbon compounds, there was a lower quantity of data (62 to 69 % or records), but data on metals were more frequently recorded for some elements i.e. chromium, nickel, lead and zinc (76 to 79 %) (Table S2).

Following Chen et al. (2024), THC values of ≤0.01 (μg/g) are at the limit of detection of many instruments so these values were set to 0 in subsequent analysis. For other records of specific hydrocarbon or metals, any negative records (indicating very low values) were set to half the minimum non-zero record. All records were subsequently log-transformed to normalize the distribution of values. A visual inspection confirmed typically higher contaminant levels within 250 m of platforms relative to values from 250 to 1500 m distant (Fig. S1). THC concentrations in the sediment correlate positively with a range of specific petroleum products and metals ($p < 0.001$, Table S3, and also Chen et al., 2024). Olsgard and Gray (1995) found that THC and Ba were the main variables correlated with effects on biota in the North Sea and Norwegian Sea and since THC is more frequently reported in the dataset than any other contaminant, we model the depletion of THC levels with distance from platforms within clusters (Figs. S2–3) and investigate the statistical relationship between THC and the biomass of benthic groups.

2.2. Environment data and clustering of platforms

Environmental information relating to sediment type per platform was available within the database (MD0: median grain size in phi units; Mud: Silt/Clay content, percentage by weight of the sub 63 μm fraction of the sediment; OM: percentage of organic content of the sediment by weight) for each study were extracted from the database. Water depth, average bottom current and distance to coast were estimated from available GIS models (Mitchell et al., 2019). The environmental datasets contained some missing values, the removal of which would have generated a smaller dataset limiting subsequent analyses. Instead, we estimated the missing values using the Data INterpolating Empirical Orthogonal Function method that iteratively decomposes the data set via Singular Value Decomposition until a best solution is found as compared to a subset of reference values (Beckers and Rixen, 2003; Taylor, 2022). This data reconstruction approach allows the study to retain all available sites for analysis while ensuring that the estimated values have minimal influence on the clustering analysis. Environmental data were scaled (z-transformation) before performing a Principal Component Analysis to characterize the physico-chemical context of each platform for which biological information is available. *K*-means partitioning (Oksanen et al., 2022) was then performed on the PCA outputs to create clusters of platforms within which we can consider environmental contexts consistent (Figs. 1 and 2). The maximum of "Simple Structure Index" (Oksanen et al., 2022) was used to identify the best number of clusters. Finally, sampling stations relating to each platform and containing the biological information and chemical values were aggregated per cluster and ordered according to distance from the platform.

2.3. Functional grouping of fauna

Mackinson and Daskalov (2007) defined functional groupings for benthic fauna whose component species are considered to have similar body sizes and share similar habitat (see supplementary material). These groupings were subsequently used in the "key-run" of the North Sea Ecopath with Ecosim model (ICES, 2016) and subsequently by Mackinson et al., 2018, Hill et al., 2021 and Püts et al., 2023. The infaunal groups consist of the following: "Infaunal macrobenthos", "Small infauna". In our dataset, Infaunal macrobenthos are generally composed of burrowing sea urchins and bivalves (such as *Echinocardium* sp. or *Arctica islandica*) (see Supplementary Data and Table S4). Small infauna are mostly comprised of polychaetes (such as *Notomastus latericeus* and *Nephtys* spp.) and small crustaceans that live in the sediment like

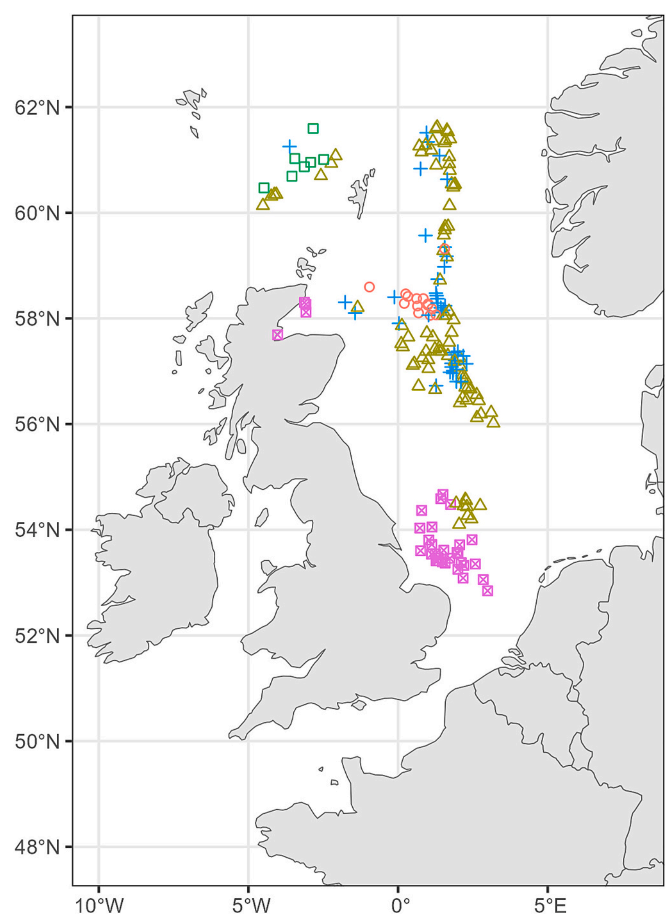

Fig. 1. Locations of platforms used in this study, coloured by clustered groupings (red = 1, green = 2, teal = 3, blue = 4, pink = 5, see Fig. 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

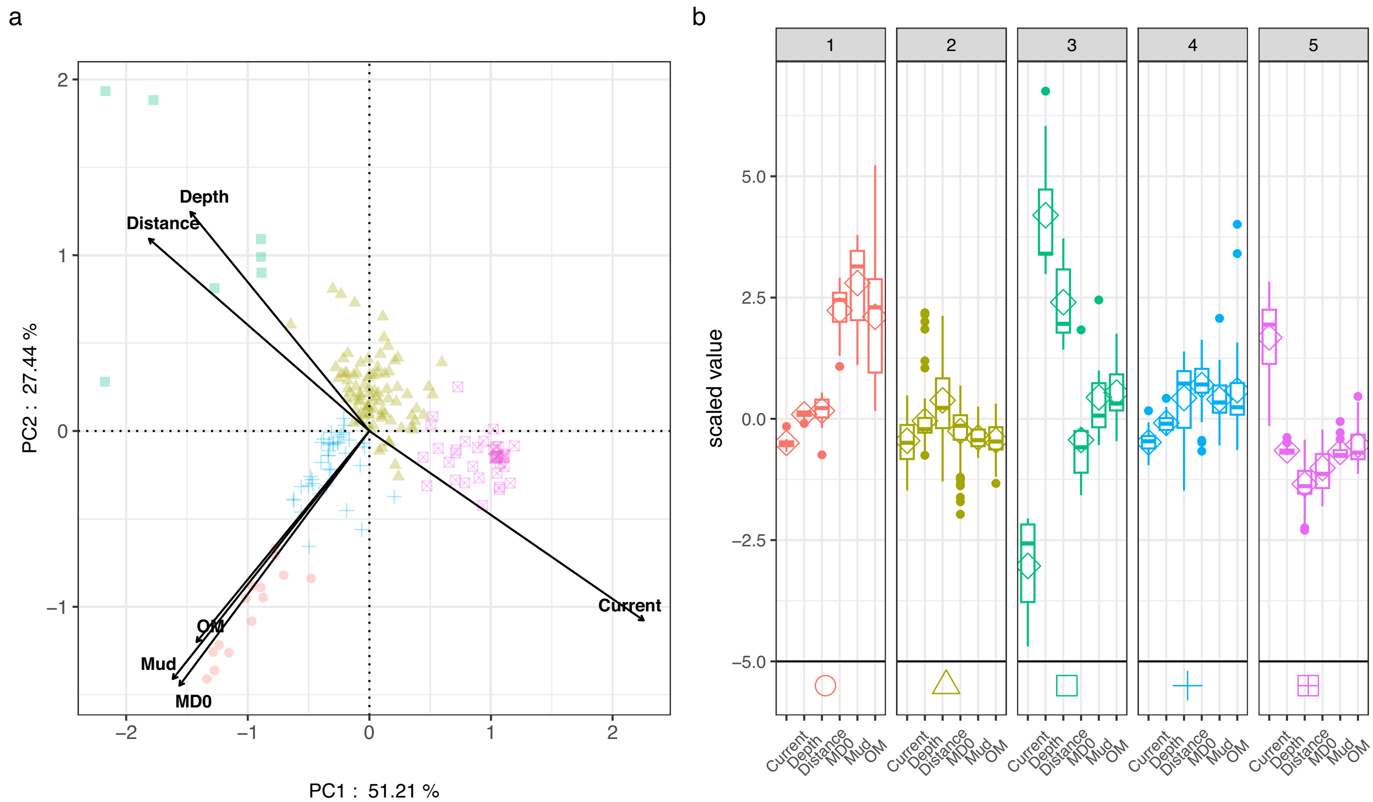

Fig. 2. a) Biplot showing the five clusters split across the first two Principal Components (PC1 and PC2), which combined explain 79 % of variability in the dataset, showing the main variables that discriminate between them. b) the environmental variables that define clusters.: Current = current velocity of surrounding seawater (m/s), Depth = seabed depth at platform location (m), Distance = distance of platform from nearest coast (km), MD0 is the median grain size (phi), Mud is the percentage Silt/Clay content by weight of the sub 63 μm fraction of the sediment (%); OM: percentage organic content of the sediment (%), all units have been scaled to allow for easier comparison.

amphipods such as *Pholoe assimilis*. The epifaunal macrobenthos group is composed of species living at the interface of the water and sediment or on top of the sediment like the gastropod *Euspira* spp., sea urchins (*Echinus* sp.) and starfish (*Astropecten irregularis*). The small mobile epifaunal group includes small amphipods (*Paraphoxus* sp., *Ampelisca* sp.), cumaceans (*Diastylis* sp) or other small crustaceans (*Tmetonyx cicada*). *Nephrops* sp., shrimps, and large crabs (including lobsters and edible crabs) are grouped separately given their particular importance in fisheries in the North Sea, but the sample data used here are considered unreliable for these groups and they are not analysed further. Similarly, the sample data were not considered reliable for meiofauna or for sessile epifauna (including Sabellidae, anemones, sponges, tunicates, bryozoans, attached bivalves such as mussels, oysters and barnacle) due to poor sampling by grabs.

The estimated biomass for each functional group considered (small infauna, small mobile epifauna, infaunal macrobenthos, epifaunal macrobenthos) was summed for each sample. Any taxa not identified within these functional groups were classed as "other" and not considered further. Biomass estimates by functional group were then averaged across samples per sampling station retaining distance from nearest platform and year of sampling. Benthic biomass data by functional group were non-normally distributed (Fig. S4), so data were transformed prior to statistical modelling using 8th root transformations for each group other than the abundant small infauna for which an 4th root transformation was sufficient.

2.4. Statistical analyses

All analyses were conducted in the 'R' software (R Core Team, 2022) version 4.3.1. For cluster 3 in the deep waters to the west of the Northern Isles, the maximum sampled level of each chemical measure was low (Tables S5 and S6), with background values of hydrocarbons recorded only, so this cluster was excluded from statistical analysis of contaminants versus distance from platform.

Initial analyses investigated whether data on chemical contaminants differed by distance from platforms, through graphing of the data and a comparison of the average of concentrations, using Welch's 2-sample *t*-tests to identify significant differences, within <250 m of the platform and between 250 m and 1500 m (Table S7). Non-linear patterns of change with distance from platforms that differed between clusters were evident in data for the concentrations of each chemical and on the biomass of benthic groups. So, data were modelled using Generalized Additive Models and Generalized Additive Mixed Models (Wood, 2004) fitted to the response data using R functions "gam" and "gamm" in package "mgcv" (Wood, 2017). In the mixed models, random intercepts were included per cluster and site grouping to account for variability unaccounted for by the environmental clustering. For chemical concentrations, the fixed effects were modelled with smooth terms to account for the non-linear relationship between response and distance to platform and the interaction with sample year (using a two-dimensional penalized tensor product spline of distance and sample year). For biomass data, the fixed effects were modelled with a smooth of total hydrocarbon concentration (Figs. S5–8), with year as a factor to account for difference over time that may not be gradual due to the pooling of multiple surveys and gear types. AIC scores were used to compare the performance of GAMMs with simpler GAMs.

From these models, we also identify general thresholds by estimating levels of contamination associated with a decline in biomass. To do so, we estimate the fixed effects of total hydrocarbon concentration (with standard error) on the biomass of each group, with random effects of cluster and site set to zero. The level of biomass depletion is determined relative to the modelled estimate of biomass at a low total hydrocarbon concentration level (10 ppm, Chen et al., 2024) in which biomass is expected to be unimpacted since a range of contaminants are expected to be low (Table S3). We set the impact-onset threshold per functional group to be the minimum value of contaminant at which the upper estimate of biomass (from the 95 % CI) is found to be equal to the minimum estimate of unimpacted biomass (from the 95 % CI of biomass at 10 ppm THC) (Fig. S9). In addition, we identify total hydrocarbon concentration levels associated with a modelled 50 % biomass depletion per functional group and cluster. We contrast the estimated onset-thresholds to the average total hydrocarbon concentration level per cluster in distance from platform categories for differing time periods to investigate whether the contaminant level in the area is likely to have led to a decrease in benthic biomass. Given the numerous tests for difference in mean values, significance is assessed at a stringent level of $\alpha = 0.01$.

3. Results

Five clusters of platforms were distinguished based on the common environmental conditions (e.g., depth and sediment grain size but excluding the contaminant data) (Figs. 1–2). Platforms in Cluster 1 are in a geographically small area in the northern North Sea characterized by low average current flow at the seabed, high mud and carbon content with a low grain size (high phi units). The environment of Cluster 2 has no features with particularly high or low values and is thus considered the base cluster and platforms in this cluster are distributed throughout the North Sea. Platforms in Cluster 3 are located west of the Northern Isles and this cluster is sited in oceanic waters with greatest water depth. Cluster 4 is intermediate between clusters 1 and 2 with platforms in the northern North Sea. Cluster 5 in the southern North Sea has platforms that are sited in shallow waters with high current flow at the seabed. The biomass of each functional group and the chemical concentrations in sediments differed between the five clusters (Table S8), where the highest mean value is a factor of 5 times the lowest for small infauna, 24 times the lowest for epifaunal macrobenthos and 31 times for THC, excluding the very low values in cluster 3.

The chemical concentrations in sediments (all measures) were significantly different from samples taken within 250 m of the platforms versus those samples between 250 and 1500 m distant (Table S7). The greatest difference was found for total hydrocarbon concentrations (the mean value for samples within 250 m from platforms was 240 ppm, while the mean of those samples taken between 250 and 1500 m was 10 ppm) followed by naphthalene (where the change was from 0.12 to 0.02 ppm). However, when data were split into early (1985 to 2001) and late periods (post 2001), a number of measures no longer maintained a significant difference between distance categories (<250 m and 250–1500 m) in the later period (specifically $p > 0.05$ for: PAH 5R mw = 252, PAH 6 ring mw = 276, barium, lead, nickel, chromium and vanadium).

3.1. General Additive Mixed Models

GAMMs and GAMs were fit to data for which both benthos and chemistry samples were available, covering the period from 1985 to 2015. All total hydrocarbon values for Cluster 3 were <100 μg/g and there were no data prior to 1998 for the cluster so these data were not included in the mixed models of contaminants. In each case the GAMM outperformed the simpler GAM so models including random effects for intercepts were retained (full results are available in the supplementary materials). Below we present the main results for total hydrocarbon concentrations in sediment (the GAMM model with highest adjusted R^2 for the fixed effects) followed by models for the biomass of each functional group.

3.1.1. Chemical concentrations in sediment vs distance and year

The model smooths were fit by using R package *mgcv* and each was significant ($p < 0.001$) in each model for each chemical investigated. Normality plots of residuals and plots of the response vs fitted values were satisfactory for total hydrocarbon concentrations (THC, Fig. S2). The fixed effects for *distance* and *year* in the mixed model of $\log_{10}$(THC) (Fig. 3) were significant with an adjusted $R^2 = 0.47$ ($n = 1236$, $p < 0.001$). An inspection of residuals revealed no patterns overall (Fig. S2). The AIC of the GAMM model with random effects was lower (AIC = 2897) and preferred over a simpler GAM model with fixed effects only (AIC = 3448). Globally, the modelled fixed effects demonstrated that THC concentration decreased with distance from that platform. However, the absolute level of the fixed effect differed by cluster with highest THC concentrations for cluster 1 (muddy habitat in the central northern North Sea), followed by clusters 2 and 4 in the central North Sea with low values for cluster 5 (high current area in the south) (Figs. 1–3). Similar patterns were evident for low molecular weight petroleum hydrocarbons, iron and zinc. The fixed effect of *distance* on THC concentrations also differed by *year*, with highest THC concentrations during the 1990s and typically low values (<100 μg/g) at and beyond 100 m from the platforms during the 2000s (Fig. 3). Despite variability in the THC data, (notably in terms of the random effect of platform, Fig. S3), modelled estimates were highest at the platforms for clusters 1, 2 and 4, where several samples displayed THC >10,000 μg/g in the period 1990–2000 (Fig. 3). In contrast, the mean THC at cluster 5 peaked at 3500 μg/g in 1995 with all THC values <100 for cluster 3.

3.1.2. Biomass of benthic functional groups vs chemical concentrations in sediment

The biomass of each functional group decreased as total hydrocarbon concentrations (as an indicator for total contamination levels from a range of contaminants) in the sediment increased (Fig. 4). The model smooths were significant ($p < 0.001$) in each model for each functional group investigated (Table S9). Normality plots of residuals and plots of the response versus fitted values were satisfactory (Figs. S5–8). Impact thresholds were established for each group relative to the expected biomass of each at a level of 10 μg/g total hydrocarbon concentration (Figs. 4 and S9). For small infauna and small mobile epifauna the impact thresholds were <100 μg/g, while for Infaunal macrobenthos the threshold was 121 μg/g and for epifaunal macrobenthos 1395 μg/g (Table S10). The concentration levels associated with a modelled 50 % biomass depletion per functional group are given in Table S11 and demonstrate differences per cluster. For example, small infauna would be depleted to 50 % of their unimpacted biomass level (as estimated at THC 10 μg/g) when THC reaches c. 300 μg/g in cluster 1, c. 700 μg/g in cluster 5, but over 1300 μg/g in clusters 2 and 4. For each functional group the 50 % depletion estimate occurred at lower THC levels in cluster 1 than any other cluster, demonstrating that the muddy habitat with low average current flow and typically low biomass of the sampled groups and highest contamination levels is most sensitive to contamination. Estimated mean total hydrocarbon concentrations from the sample data within 500 m of platforms in the period 1985–2001 were above the onset-thresholds for each group in clusters 1, 2 and 4 (with the exception of epifaunal macrobenthos in clusters 1 and 2) suggesting likely impact (Fig. S10). In clusters 2 and 4, the biomass of all functional groups was significantly lower ($p < 0.01$) within 500 m of platforms in the early period (Fig. 5). In cluster 1, the biomass of small mobile epifauna, the most sensitive group, was significantly lower within 500 m of platforms.

In the later period 2002–2015, the mean THC values in clusters 2 and 4 fell below the onset thresholds for every functional group (<22 ppm) and, correspondingly, the biomass of all groups in cluster 2 and all except infaunal macrobenthos in cluster 4 were no longer significantly different between the distance categories, suggesting possible recoveries following decreases in contaminants as indicated by THC (Fig. 6). Mean THC values remained elevated in cluster 1 (114 ppm) relative to the

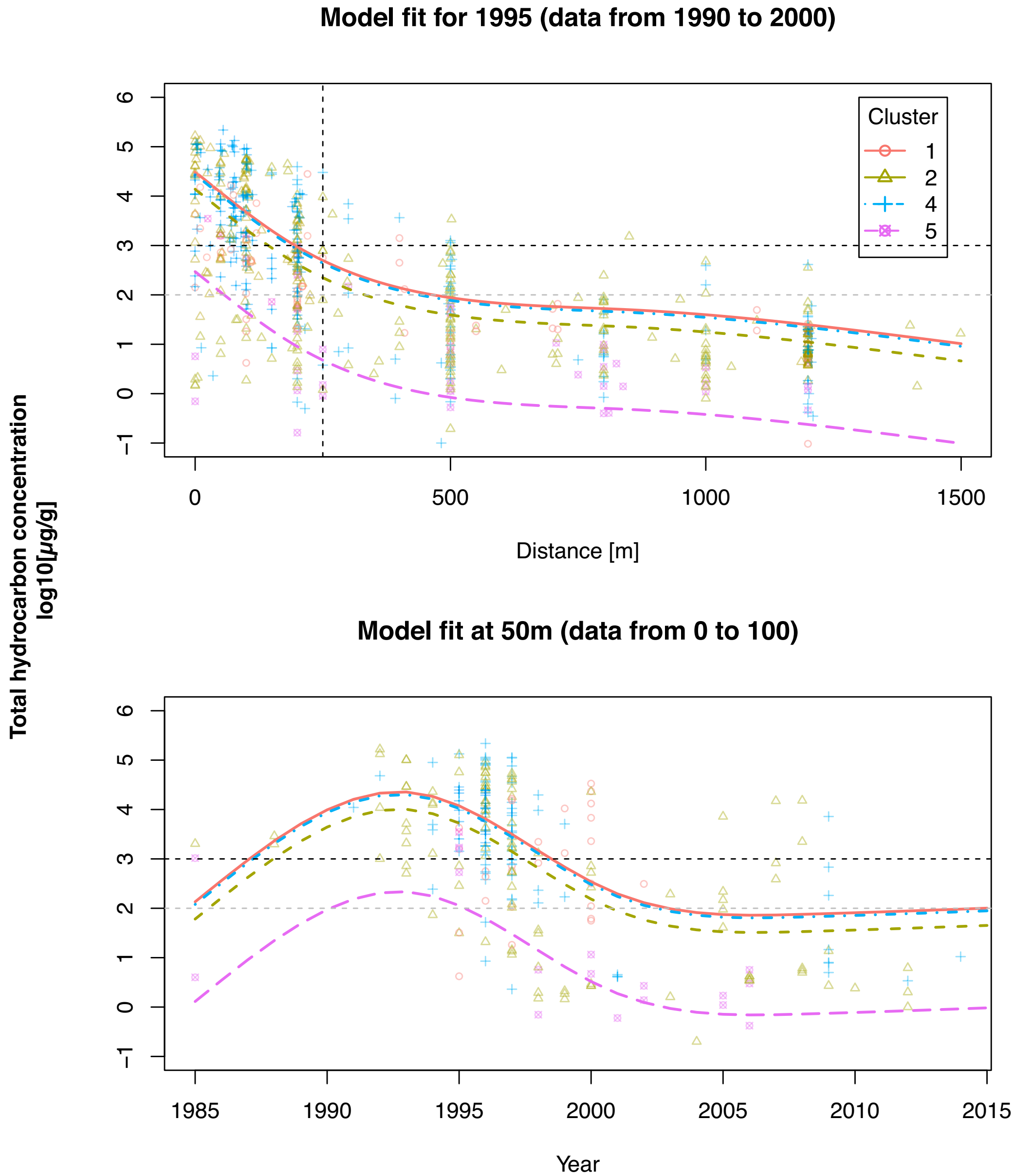

Fig. 3. Total hydrocarbon concentration (THC) measurements in sediment [log10(μg/g)] (points) plotted against distance from platforms (top) and year (bottom). Fitted lines (fixed effects plus random effects) and data points are coloured according to the environment-based clusters as shown in Fig. 1. The horizontal dashed lines are drawn at 100 μg/g (gray) and 1000 μg/g (black) for visualization, while the vertical black dashed line is drawn at 250 m (top only). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

onset-threshold for two groups (small infauna and small mobile epifauna) and their biomass were found to be significantly depleted within 500 m, in line with the expectation.

The mean THC data for clusters 3 and 5 demonstrates that the levels were below the onset thresholds for each group and in each period and distance category considered. In each period considered, only one of each of the ten tests found a significance difference between distance categories (small infauna in cluster 5 in the early period and small mobile epifauna in cluster 3 in the late period). However, the number of benthic samples in each distance category were low in cluster 5 ($N < 20$, Table S12) and very low in cluster 3 ($N < 10$). Similarly, in cluster 1, the biomass of 4 of 5 functional groups were not significantly different between distance categories in each time-period as expected, but again sample size was very low.

4. Discussion

Total hydrocarbon concentrations (THC) are often considered within guidelines for sediment quality in relation to potential contamination (e.g. Bjørgesæter and Gray, 2008) and, although no single value is considered appropriate for all sediment types and water depths, a general threshold of 50 μg/g was considered by UKOOA (2002) below which no significant environmental threat is likely. Indeed, at offshore oil and gas platforms on the Norwegian continental shelf, benthic macrofaunal disturbance has been reported in locations where THC > 50 μg/g (e.g. Beyer et al., 2025). However, the empirical study of Bjørgesæter and Gray (2008) reported effects on benthic fauna at sites with THC as low as 5 μg/g for clay in depths >300 m. In contrast, Bjørgesæter and Gray (2008) found effects on benthic fauna were only detectable >75 μg/g in very fine sands between 100 and 300 m. This study has demonstrated five distinct clusters of platforms in the North Sea that differed in terms of the environmental conditions (sediment

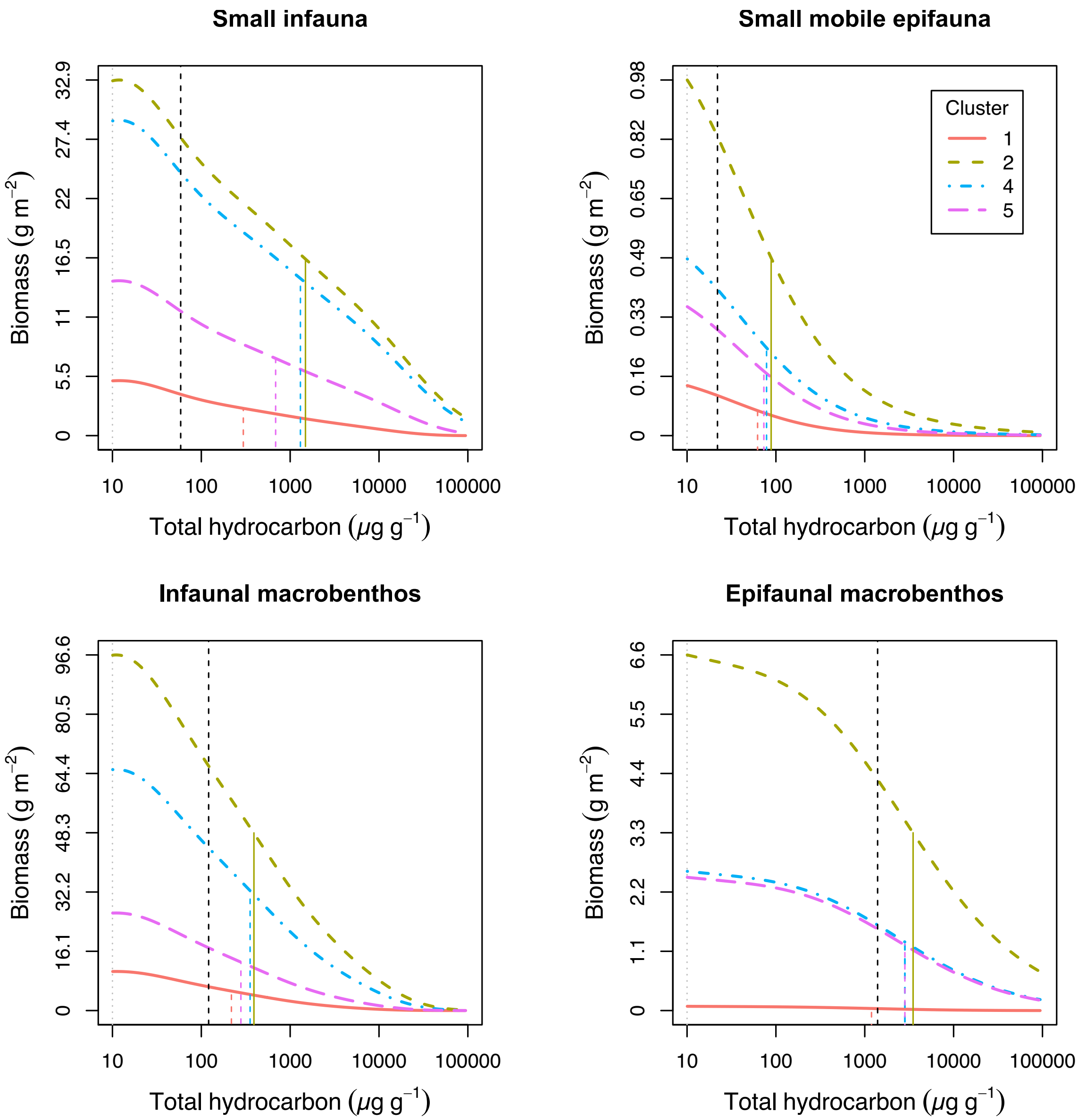

Fig. 4. Modelled biomass [g m^{-2}] of functional groups of benthos due to cumulative effects of contaminants as indicated by the total hydrocarbon concentration in the sediment. Fitted lines are coloured according to the clusters shown in Fig. 1 and are evaluated based on the average random effect of sites within cluster. Vertical lines are drawn at 10 μg/g (dotted gray) along with the impact-onset threshold (dashed black, Table S10) and 50 % impacted levels per group (coloured lines, Table S11). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

type, depth and current velocity) at the locations of the platforms. Mixed models were employed to correct for the effect of these environmental conditions on the statistical relationship between distance from platform and contamination as indicated by THC. This study demonstrated how the decrease in the biomass of each faunal group could be identified statistically and found that small infauna and small mobile epifauna were more sensitive to contamination (with an onset of decrease in biomass that begins at a lower THC level <60 μg/g than the macrobenthic groups). In contrast, the modelled onset of decrease in the biomass of epifaunal macrobenthos occurs at levels >1000 μg/g only and these species can be considered least sensitive to effects of contamination. We do not identify the mechanisms that lead to a decrease in biomass and we are using THC here as an indicator of overall contamination levels due to the correlation between this variable and the multiple contaminants that it is associated with (such as barium, zinc and specific hydrocarbon compounds, see Table S3). The benthic functional groupings were considered by Mackinson and Daskalov (2007) as relevant prey groupings for benthivorous predators given that their feeding modes are adapted to exploiting particular sized prey in particular habitats. Lynam et al. (2017) and Püts et al. (2023) used these groupings within Ecopath and Ecosim to model spatial responses to the presence of platforms. As these groups are well studied, the relationships between biomass and contaminants detected within the present work can more easily relate to a change in the wider food-web compared to a more conventional species-based approach. The results presented here suggest there can be an impact of contamination on seabed communities, particularly on the infauna, that may differ between body sizes, which extends beyond the immediate physical impact of the platform to an extent that depends on the environmental conditions. However, our results for epifauna near oil and gas platforms do not exclude the possibility of higher biomass on the platform above the seabed, which could outweigh the impact on biodiversity of construction and potential contamination during operation. However, the data investigated were exclusively from grab and core samples (that poorly sample the larger epifauna) at the base and in the vicinity of oil and gas platforms and so are biased towards soft-bottom benthic fauna and smaller individuals.

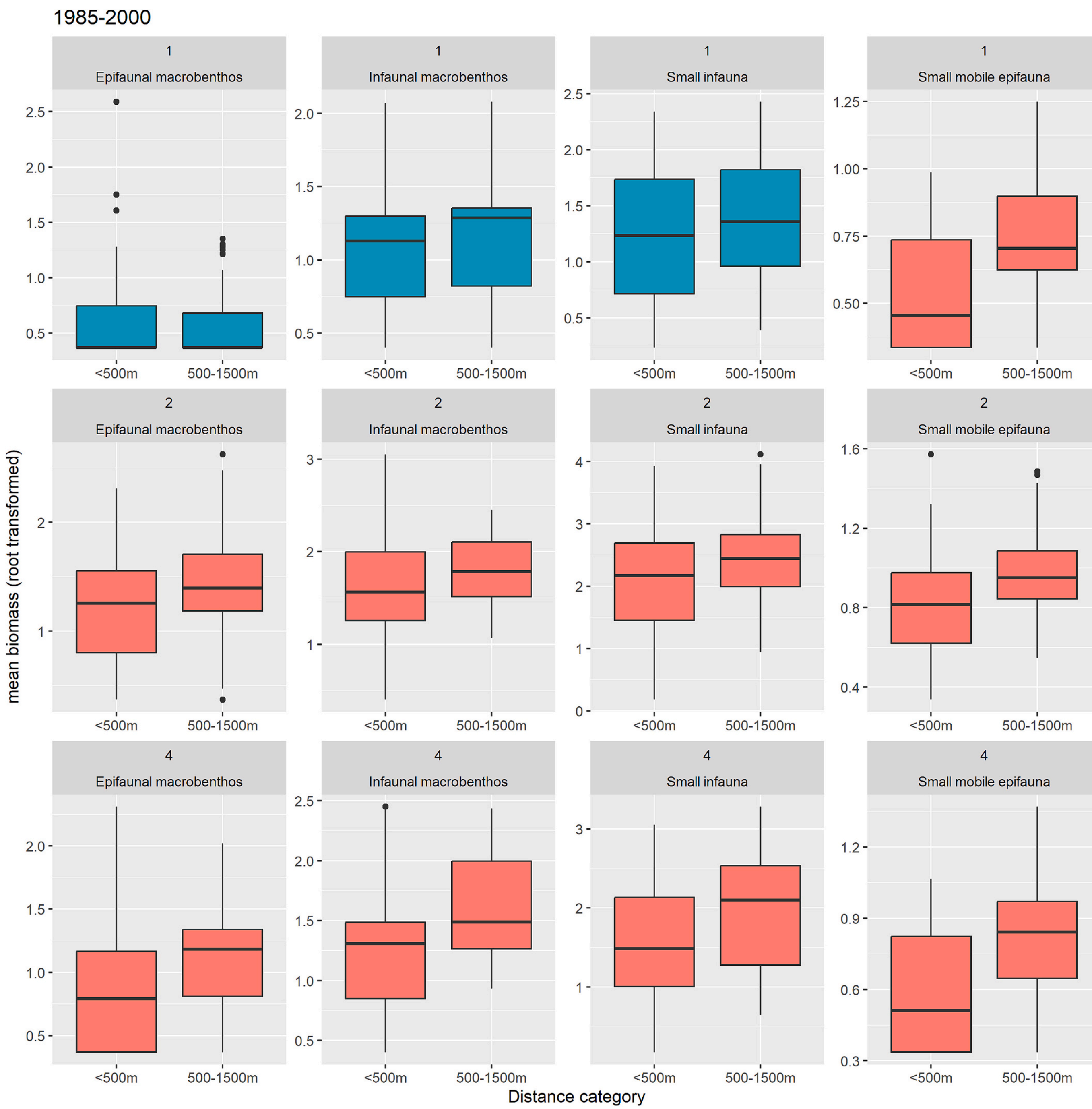

Fig. 5. Change in transformed mean biomass [g per m^2] of functional groups by distance category based on sample data between 1985 and 2001. Boxplot pairs are coloured red for significant ($p < 0.01$) Welch's two-sample *t*-test (one-sided) i.e. test that the sample mean for the distance category <500 m is lower than the mean for the distance category 500–1500 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, our results suggest that smaller organisms of both infauna and epifauna are more sensitive to impacts of contamination than larger organisms. Our pooled dataset includes platforms that have been decommissioned and platforms that are still operating, but our results link benthic biomass levels to contamination in sediments measured concurrently.

Total hydrocarbon concentrations in cuttings piles in North Sea sites can range from 10,000 to 600,000 μg/g (Bakke et al., 2013), the same levels found here in sediment sample data during the 1990s from clusters 1, 2 and 4 within 250 m of the platforms and particularly within 100 m (Fig. 3). However, the value recorded depends on depth since surface values are typically much lower than values at the centre of the pile (Terlizzi et al., 2008). Hartley (1996) demonstrated that contamination levels of barium, zinc and lead in the seabed decreased with distance from a well head drilled for oil and gas exploration with highest values in the cuttings pile that built up between 10 m and 50 m of the well head. Similarly, Chen et al. (2024) demonstrated that contamination levels of hydrocarbons and metals were higher within 500 m of 9 well sampled oil and gas platforms across the North Sea (using a subset of the data modelled in this study) and also that benthic biomass was lower near to platforms. So, the observation here that contaminants are in general higher near to oil and gas platforms are not surprising. However, we have demonstrated that these detrimental impacts on the biomass of benthic functional groups hold more widely across a large dataset and,

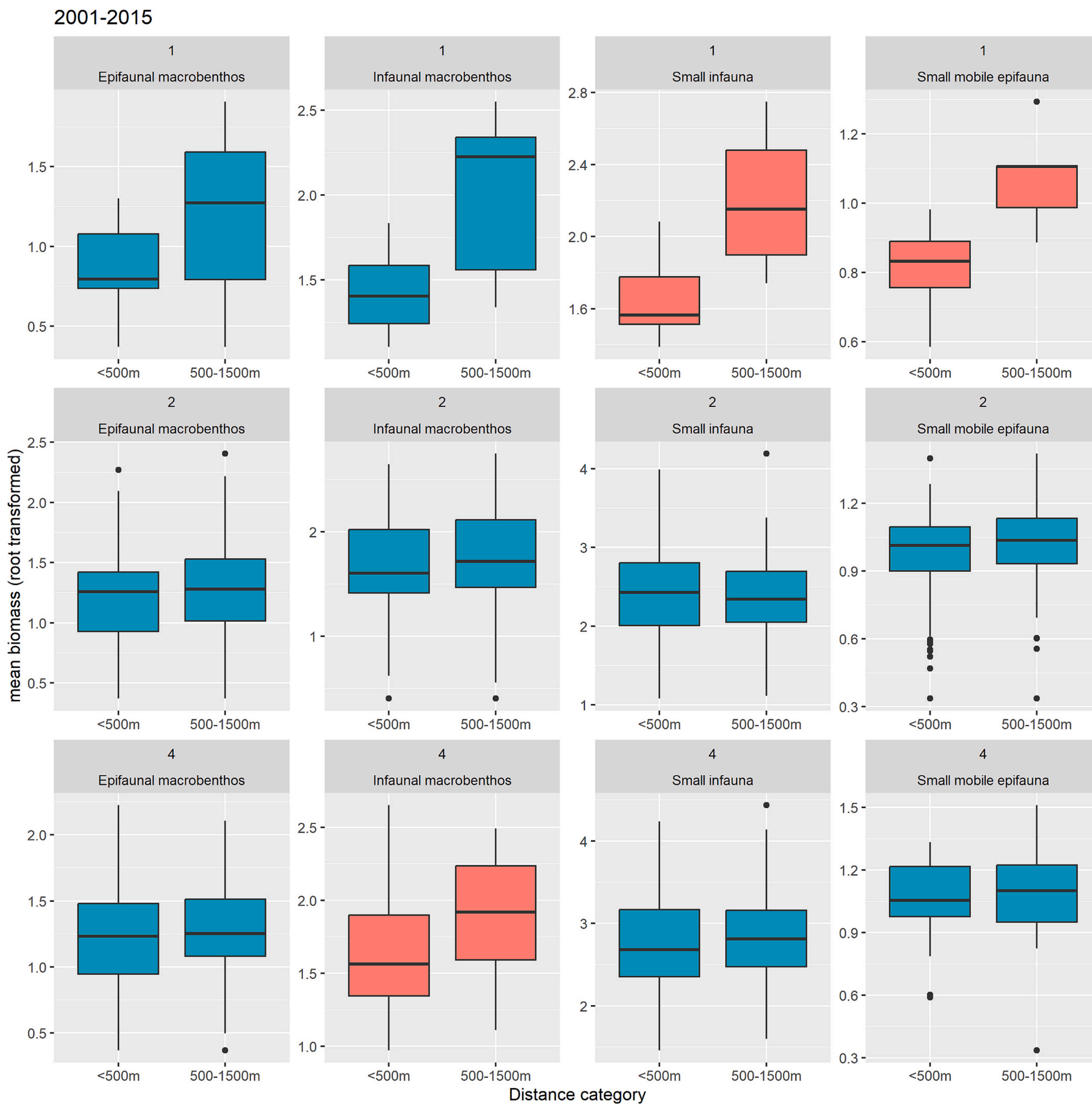

Fig. 6. Change in transformed mean biomass [g per m^2] of functional groups by distance category based on sample data between 2002 and 2015. Boxplot pairs are coloured red for significant ($p < 0.01$) Welch's two-sample *t*-test (one-sided) i.e. test that the sample mean for the distance category <500 m is lower than the mean for the distance category 500–1500 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

importantly, have reduced over time following management action during the 1990s (OSPAR, 2000) and the change by the industry to synthetic drilling muds such that subsequent recovery is evident.

In our study, samples were grouped within the clusters, but temporal changes were not investigated specifically for each platform due to a lack of repeated sampling over time for each site. Therefore, we are not able to know at what stage of operation or macrofaunal recovery the data arise from, which is worthy of further study, so we recommend additional data on time since construction is added to the database. It is likely that the benthic communities are not stable and may continue to change over time, which can contribute to the variability in the data. Nevertheless, our study was able to detect strong patterns of change in biomass and hydrocarbon contamination that were highly significant.

We found THC in sediment samples were low in the deep waters west of the Northern Isles (cluster 3) and in the south-western North Sea (cluster 5) relative to samples from other clusters suggesting a lack of pollution in these areas. In the south-western North Sea, a lack of extensive cumulations of cuttings material could also be attributed to high tidal and storm driven current flows advecting material (Bakke et al., 2013). Furthermore, the finer particle size of sand in the hydrodynamically active area of the south-western North Sea is likely to disperse any contamination level more rapidly than the muddier sediments of the other clusters (Owens et al., 1994).

Although the biomass of many benthic groups were lower near to platforms (<500 m) and at high contaminant concentrations (in clusters 1, 2 and 4), and contaminant levels were found to increase near to platforms, these depleted biomass levels could also be the result of the physical impacts from drilling and the construction phases. Furthermore, the level of toxicity of the hydrocarbons was not investigated.

A potential impact on infauna by benthivorous predators, such as the highly abundant dab *Limanda limanda* (ICES, 2022), can also not be eliminated by this study. This is particularly the case within the safety zone (<500 m) in place around the platforms during active operation which prohibits fishing activities, acting as a de-facto Marine Protected Area, which may allow prey species to increase and subsequently attract predators to the area. Fishery exclusion areas around active oil and gas sites will also prevent direct impact of fishing on the fauna and sediment. Furthermore, oil and gas platforms have been shown to increase benthic biodiversity by providing artificial reefs for epifauna such as anemones (e.g. plumose anemone, *Metridium senile*) and corals (e.g. stony coral, *Lophelia pertusa* and dead man's fingers, *Alcyonium digitatum*) (Guerin et al., 2007; Dannheim et al., 2020; Redford et al., 2021; Todd et al., 2018). These platforms may also act as stepping-stones for the spread of some species, which can influence the distribution of both native (Friedlander et al., 2014) and non-native species (Yeo et al., 2010). So, a trade-off in pressure from the presences of platforms and associated contaminants and the lack of demersal trawling pressure (typically within 500 m) from the platform provides added complexity to ecosystem responses. Therefore, drawing a simple mechanistic causal link between the observed faunal responses to platforms, is problematic due to several indirect, confounding factors. However, our use of a large-pooled dataset across the North Sea in different environmental conditions has found differences in THC levels that range over four orders of magnitude. Importantly, in areas where contaminants have decreased in the sediment the majority of impacted functional groups has increased in biomass comparable to reference conditions. This agrees with Beyer et al., 2025 who report that the implementation by managers of the decisions agreed internationally by PARCOM and later OSPAR has contributed to the recovery of the benthic communities in these habitats.

The data contained within the Oil and Gas UK database may be used, as has been demonstrated here, to inform future decisions regarding the most suitable decommissioning options for a given platform. As we have shown, some platforms display elevated sediment THC concentrations in their vicinity and a resulting correlative link with the biomass of infaunal functional groups. However, to determine likely effects of contaminants on fauna it is important to know the amount of toxic hydrocarbon compounds that are present and the differing susceptibility of the various organisms to them (National Research Council, 2003). The decommissioning of these platforms (OSPAR, 1998) should explicitly consider this potential causal link and the potential for decommissioning to lead to the release of sediment-bound contaminants into the wider marine environment. Current practice requires complete removal, which may resuspend and potentially spread contaminants and in addition to physical disturbance may impact the benthos.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118470.

CRediT authorship contribution statement

Christopher P. Lynam: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Clement Garcia:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Zelin Chen:** Methodology, Data curation. **Gareth E. Thomas:** Writing – review & editing, Data curation, Conceptualization. **Natalie Hicks:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Stefan G. Bolam:** Writing – review & editing, Methodology. **Debbie J.F. Russell:** Writing – review & editing, Methodology, Funding acquisition.

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.

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Data availability

OGUK Database of Offshore Environmental Surveys (Original data) (OGUK)

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