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RESEARCH ARTICLE

Increased benthic biodiversity and food web recovery after decommissioning of oil and gas infrastructure

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Abstract

There is a global increase in the decommissioning of offshore oil and gas (O&G) infrastructure at the end of its operating lifetime. However, there is strikingly limited empirical evidence for the environmental and ecological impacts of decommissioning. Here, we employed a meta-analytical approach on an industry benthic monitoring database to investigate the benthic biodiversity and food web properties of structures sampled in the short term (< 1 yr; scenario 1), medium term (1–5 yr; scenario 2), and long term (> 5 yr; scenario 3) after decommissioning. We found reduced species richness and simplified food webs in scenario 1, followed by the first signs of recovery in scenario 2, with a slightly higher proportion of intermediate species and density of food web connections. Food webs recovered further in scenario 3, with a much greater density of interactions, but also more links and longer food chains, while a reduction in generalism and connectance indicated an increased prevalence of specialist species. Our findings demonstrate disturbance risks associated with the decommissioning process in the short term, but a positive recovery trajectory over longer timescales. We highlight the importance of industry collecting more extensive and long-term data at multiple time points and covering different decommissioning types, establishing a standardized data workflow for integrating with available monitoring efforts, and improving stakeholder participation and data accessibility to support an environmentally sound decommissioning process.

Offshore oil and gas (O&G) infrastructure has a major presence in the global shelf seas, with > 12,000 documented structures operating in 2022 (Martins et al. 2023). As O&G reserves are depleted, > 7500 O&G structures are approaching the end of their economic and operational purposes (Parente et al. 2006). The term "decommissioning" generally refers to the process from cessation of production to the removal of obsolete infrastructure (Melbourne-Thomas et al. 2021). In many regions, legislation prohibits the dumping of whole or partial O&G infrastructure, and thus complete removal is required (Fowler et al. 2020). Despite the pressing need for decommissioning of O&G infrastructure in the near future, there is limited understanding of environmental and ecological consequences, calling for a greater evidence base to support best practice in decommissioning.

Current removal policies regard O&G infrastructure as redundant and aim at restoring the marine environment to its pre-exploitation state through complete removal of structures. However, this largely ignores the change in ecological context due to the long-term presence of O&G infrastructure, with little empirical evidence for whether complete removal is beneficial or whether it could be an even greater disturbance to marine ecosystems (Fowler et al. 2020). Conversely, the decadal presence of infrastructure has integrated hard-substrate habitats into environments dominated by soft sediment, supporting the settlement of epifaunal communities and associated biodiversity and ecosystem services not originally present locally (van der Stap et al. 2016). For example, O&G infrastructure enhances biodeposition processes from epifaunal filter feeders which increase organic matter flux in the sediment near the structure, potentially leading to a higher density and diversity of

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macrofaunal communities, particularly for fragile and long-lived benthic invertebrates sensitive to trawling (Coates et al. 2014). Furthermore, the exclusion of fishing activities around O&G infrastructure provides shelter for fish assemblages, which in turn attracts marine mammals and other top predators as foraging grounds (Russell et al. 2014; Fujii 2015). O&G structures can act as stepping stones for native and non-native species, modifying the connectivity of planktonic larvae (van der Molen et al. 2018). What is clear is that the removal of O&G infrastructure, whether structures, wells, or pipelines, will likely alter associated physical and ecological processes currently occurring in and across marine areas impacted by O&G exploitation, and it is not fully clear that removal is more beneficial for the marine ecosystem than the pre-infrastructure state.

The major negative environmental and ecological impacts of O&G structures come from discharges of O&G-associated contaminants during the O&G operating phase (MacIntosh et al. 2021). The primary source of contaminants are discharges of produced water and drill cuttings (Bakke et al. 2013). Produced water consists of formation water that becomes contaminated during extraction, containing dissolved hydrocarbons, heavy metals and other pollutants (Neff et al. 2011). This water is discharged during O&G activity and operation, often creating a plume in the water column, with heavier particles settling on the sediment. This plume contains hydrophobic compounds which may attach to sediment particles before being dispersed within the water column (Marappan et al. 2022). Drill cuttings are rock fragments and sediment debris brought to the surface in the drilling, which are typically soaked with petroleum residues and drilling lubricants that also contain hydrocarbons, heavy metals, and barite (Ellis et al. 2012). Depending on local hydrodynamics and volume discharged, the accumulation of contaminants could extend up to 6000 m from the infrastructure (Olsgard and Gray 1995). Elevated concentrations of hydrocarbons and heavy metals have been observed above the environmental quality guidelines for threshold concentrations (Altin et al. 2009). Major adverse impacts on biotic communities generally occur within 500 m of the structure, with modified community composition and simplified food webs (Chen et al. 2024). Changes in food web structure are of great importance in assessing ecosystem status because they reflect not only shifts in community composition but also the reorganization of trophic interactions that underpin ecosystem functioning (Nagelkerken et al. 2020). Simplified food webs indicate fewer energy pathways and less efficient energy fluxes, whereas greater complexity in trophic structure is generally associated with greater resilience to secondary extinction (O'Gorman et al. 2019). Therefore, quantitative analysis in food web structure, combined with diversity analysis, provides a more comprehensive insight for assessing the ecological consequences of O&G decommissioning.

Physical decommissioning typically occurs after cessation of production and when drilling and production activities are suspended. It involves well plugging and abandonment, dismantling and removal of facilities, and site remediation (Fam et al. 2018). The termination of O&G exploitation halts the release of associated contaminants, subjecting residual contaminants to dissipate or undergo remediation over time (Dell'Anno et al. 2021). As contamination stress declines, benthic communities are expected to gradually transition toward background assemblages characteristic of local soft-bottom habitats with minimal influence from O&G activities (Fortune and Paterson 2018). Compared to the baseline during the O&G operation phase, benthic recovery is anticipated to produce a more diverse community (i.e., higher species richness) and a more complex food web structure (i.e., increased trophic interactions and greater trophic height). Although physical removal may be beneficial in the long term, the physical disturbances introduced during decommissioning can impose short-term risks to benthic invertebrates near the structures, yet few quantitative assessments have examined these impacts. For example, the use of explosives and cutting tools during structure removal can physically disturb organisms through burial, alter sediment composition, generate noise and vibration, and increase turbidity in the water column (Burdon et al. 2018). While environmental impact assessments of decommissioning practices generally concluded no significant long-term environmental harm, it remains uncertain whether short-term disturbances further stress marine organisms prior to recovery, as this impact has not been directly measured (Lakhal et al. 2009). In soft-sediment communities, recovery rates depend on the ecological state at the onset of decommissioning, larval and adult species dispersal, residual contamination, and other disturbances such as trawling (Schroeder and Love 2004). Studies of post-exploitation biological recovery suggest that the restoration of ecosystem functionality typically requires 5–10 yr (Gates and Jones 2012; Henry et al. 2017).

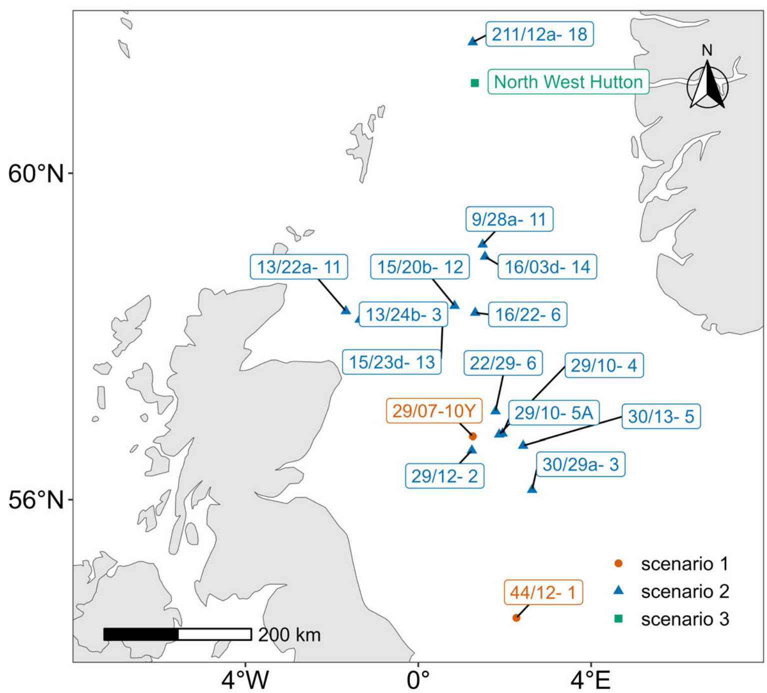
In this study, we quantified the effects of decommissioning on sediment contamination and ecological responses of benthic invertebrate communities by comparing pre-decommissioning (operating phase) and post-decommissioning conditions, using a before-after-control-impact (BACI) design. Marine benthic invertebrates have been widely used as biological indicators to measure ecological quality in the marine environment and assess the consequences and magnitude of a variety of natural and anthropogenic disturbances (Borja et al. 2000). Their relatively sedentary characteristics and variable tolerances to stress make benthic invertebrates ideal to examine the gradient of decommissioning impacts. We distinguish between two processes that may influence the onset of recovery: (i) the cessation of O&G operational pressures (e.g., contamination discharge) once production ceases, and (ii) the short-term, localized physical disturbance caused during the decommissioning activities. Since decommissioning marks the end of O&G exploitation and associated operational disturbances, we expect an improved chemical status in benthic sediment and a shift in benthic biodiversity and food web structure toward the background environment. In contrast, the physical disturbance associated with decommissioning may cause immediate negative impacts, so recovery of benthic communities is more likely to be detected in the medium to long term rather than immediately after decommissioning. Therefore, we hypothesize that decommissioning of O&G infrastructure will cause: (1) reduced concentrations of hydrocarbons and heavy metals in the sediment; (2) increased total abundance and species richness; and (3) greater food web complexity; but with effects realized in the longer term after decommissioning.

Materials and methods

Data compilation

Biological and chemical data were obtained from the UK O&G industry from the published UK Benthos database of offshore environmental surveys: UK Benthos database v5.17 (Offshore Energies UK 2015). This database contains data from over 700 benthic monitoring surveys from 1975 to 2015, with samples for more than 250 O&G structures across the North Sea and North Atlantic margin. As such, the sampling design and spatio-temporal scale vary across structures in the database: No single O&G structure in the dataset was consistently sampled throughout its life cycle; some were revisited at two different time points before and after decommissioning, while others were sampled post decommissioning at multiple time points. Most surveys included both impact (< 500 m from the structure) and control samples (> 500 m), but the exact distances and number of replicates varied among surveys. Following Chen et al. (2024), we defined the impact zone for samples collected within 500 m, while the control zone for samples collected beyond 500 m.

Based on data availability and their sampling design, we defined three scenarios for a total of 17 structures to assess decommissioning effects: **short-term** (scenario 1, < 1 yr post-decommissioning), **medium-term** (scenario 2, 1–5 yr post-decommissioning), and **long-term** (scenario 3, > 5 yr post-decommissioning) (Fig. 1). Note that both scenarios 1 and 3 contained samples before and after decommissioning, while scenario 2 contained samples at two or more time points post-decommissioning. The commencement and decommissioning dates for each structure were obtained from industry reports and a regulatory database (North Sea Transition Authority 2024). These dates were used to define the period of



Scenario	Sampling design	Comparison baseline	Count	Ecological interpretation
1	Before Decomm -> After Decomm (<1 yr)	Operating status	2	Short-term recovery
2	Early Post Decomm -> Later Post Decomm (1-5 yrs)	Early post-decomm status	14	Medium-term recovery
3	Before Decomm -> After Decomm (>5 yrs)	Operating status	1	Long-term recovery

Fig. 1. Locations of the eligible O&G structures that were used to compare before decommissioning and short-term post-decommissioning (orange circles), early and later post-decommissioning recovery in the medium term (blue triangles), and before decommissioning and long-term post-decommissioning (green squares).

operation for each structure. For scenario 1, there were 2 structures containing 66 samples (29 in the impact and 10 in the control zone before decommissioning; 21 in the impact and 6 in the control zone after decommissioning). For scenario 2, there were 14 structures containing 384 samples (134 in the impact and 52 in the control zone at the early time point after decommissioning; 147 in the impact and 51 in the control zone at the later time point after decommissioning). For scenario 3, there was 1 structure containing 21 samples (7 in the impact and 5 in the control zone before decommissioning; 4 in the impact and 5 in the control zone after decommissioning).

Entries of species names and their taxonomy classifications were verified against WoRMS (WoRMS Editorial Board 2023). There were 995 unique benthic taxa included in our analysis: 74% ($n = 739$) were at the species level, 19% ($n = 189$) at the genus level, and the remaining 7% ($n = 67$) were at the family level. Taxa higher than family level ($n = 82$) were excluded due to uncertainty in assigning feeding groups and building food webs. We assigned an estimated individual body mass to each taxon using a biological trait database of Northwest European benthos (Clare et al. 2022). Total biomass for each sample was then calculated as the sum of taxon-specific biomasses (body mass $\times$ abundance for each taxon). From this, we estimated an abundance-weighted mean individual body mass of invertebrates for each sample by dividing total biomass by total abundance. We then calculated three diversity metrics of interest: total abundance, species richness, and Pielou's evenness. The mean individual body mass at each sample was calculated by dividing total biomass by total abundance. The joint use of total abundance, mean individual body mass, species richness, and Pielou's evenness provides a holistic assessment of benthic biodiversity with complementary metrics that are commonly used in other studies (Ryu et al. 2011; Coolen et al. 2022). Total abundance reflects the overall number of individuals in the community; mean individual body mass characterizes the average size of all the organisms in the community; species richness is the number of unique taxa; and Pielou's evenness measures the distribution of abundance across taxa.

As our study focused on benthic invertebrates living on or in the sediment around structures, more mobile organisms like fish, mammals, and pelagic species were not included in the diversity analysis and food web construction. Each taxon in our dataset was assigned to one of six feeding groups based on its primary prey and distinct feeding characteristics: detritivore, filter feeder, grazer, scavenger, parasite, and predator. We assumed the pervasive existence of nine basal resources at all sampling sites (i.e., carrion, bacteria, CPOM, feces, FPOM, fungi, macroalgae, microalgae, and protists) and assigned subsets of those basal resources to primary consumers: detritivores, filter feeders, grazers, and scavengers (*see* Supporting Information Fig. S1). Interactions for predators (organisms that actively hunt for prey) and parasites (organisms that feed on hosts without directly killing them) were determined from previous dietary studies in the literature. Trophic interactions were established at the taxon level using a metaweb approach, that is, local food webs were drawn from a regional database of interactions for the North Sea compiled by Chen et al. (2024). For each sample, the local food web was constructed as the subset of trophic interactions from this metaweb for taxa observed in that sample. For taxa lacking species-specific diet information, interactions were inferred from published data at higher taxonomic levels (e.g., genus or family). Since 89% of taxa in our dataset are resolved to the species or genus level, we considered our metaweb approach to be robust for reflecting biodiversity and food web responses. We calculated the following nine food web metrics using the "*cheddar*" package in R: proportions of basal, intermediate, and top species, mean trophic level, standard deviations of normalized generality and vulnerability (herein referred to as generality and vulnerability), link richness, linkage density, and connectance (Hudson et al. 2013). Proportions of basal, intermediate, and top species describe the trophic distribution of taxa throughout the food web. Mean trophic level characterizes the average vertical position of a taxon in the food web and can be thought of as the typical distance that energy is transferred from basal resources to organisms at higher trophic levels. Generality and vulnerability reflect the average number of prey and predators, respectively, of each taxon in the food web. The number of links reflects the size of the food web, linkage density is the average number of links per taxon, and connectance is a measure of food web complexity that is often associated with the resilience of the system to external perturbations. The integration of these well-defined metrics provides a holistic exploration of how food web structure changes in response to O&G decommissioning.

Concentrations of hydrocarbons and heavy metals in the sediment were measured for every sample of benthic taxa (micrograms per gram sediment, $\mu g\, g^{-1}$). Total hydrocarbon concentrations were determined by gas chromatography, and five metals were measured, including barium, copper, nickel, lead, and zinc. We summed up concentrations of copper, nickel, lead, and zinc as a proxy of total heavy metal concentration, while barium, extracted by sodium fusion and other similar methods, represents total concentration present in the environment regardless of its chemical form or availability to marine organisms and was therefore considered separately. Any concentration values of hydrocarbons and heavy metals below the threshold for detection of 0.01 $\mu g\, g^{-1}$ were assigned a value of 0.

Experimental design

To account for background environmental changes unrelated to decommissioning, we classified samples within 500 m of each structure as impact and those beyond 500 m as control. The threshold was selected based on recent evidence showing no major differences in hydrocarbon concentrations in sediment beyond 500 m (Chen et al. 2024). Recovery signals were assessed with a difference-in-differences (DiD) design (Fig. 2). For scenarios 1 and 3, changes in the impact were calculated as the difference between post- and pre-decommissioning values, whereas for scenario 2, changes were calculated as the difference between later and earlier post-decommissioning observations. Concurrent changes in the control were subtracted to isolate decommissioning effects. The DiD approach compares mean changes in impact and control samples—before and after decommissioning in scenarios 1 and 3, or between early and later post-decommissioning stages in scenario 2—thereby isolating decommissioning effects from background temporal variability and allowing consistent comparisons across structures with heterogeneous sampling histories (Wing et al. 2018).

The DiD approach aims to compare mean impact changes and control changes, both before and after decommissioning in scenarios 1 and 3 or in both the early and later stages post-decommissioning in scenario 2, to assess decommissioning effects while taking account of background variability through time. The net intervention effects (Δ) of decommissioning or post-decommissioning recovery were calculated as follow:

$$\Delta = \left(\overline{impact}_{after} - \overline{impact}_{before}\right) - \left(\overline{control}_{after} - \overline{control}_{before}\right) \quad (1)$$

where $\overline{impact}_{before}$ and $\overline{impact}_{after}$ represent means of the impact before and after intervention, while $\overline{control}_{before}$ and $\overline{control}_{after}$ represent means of the control before and after intervention. Hedge's g effect size was then calculated as a standardized measure to quantify the significance and magnitude of the net intervention effects, while considering a correction for small sample sizes at each O&G structure ($n < 30$) (Cohen 2013).

$$\text{Hedge's}\, g = \frac{\Delta}{Variance_{pooled}} \times \left(1 - \frac{3}{4(N-2)-1}\right) \quad (2)$$

where N is the total number of samples across the impact before, impact after, control before, and control after decommissioning, and $Variance_{pooled}$ is the pooled standard deviation calculated as:

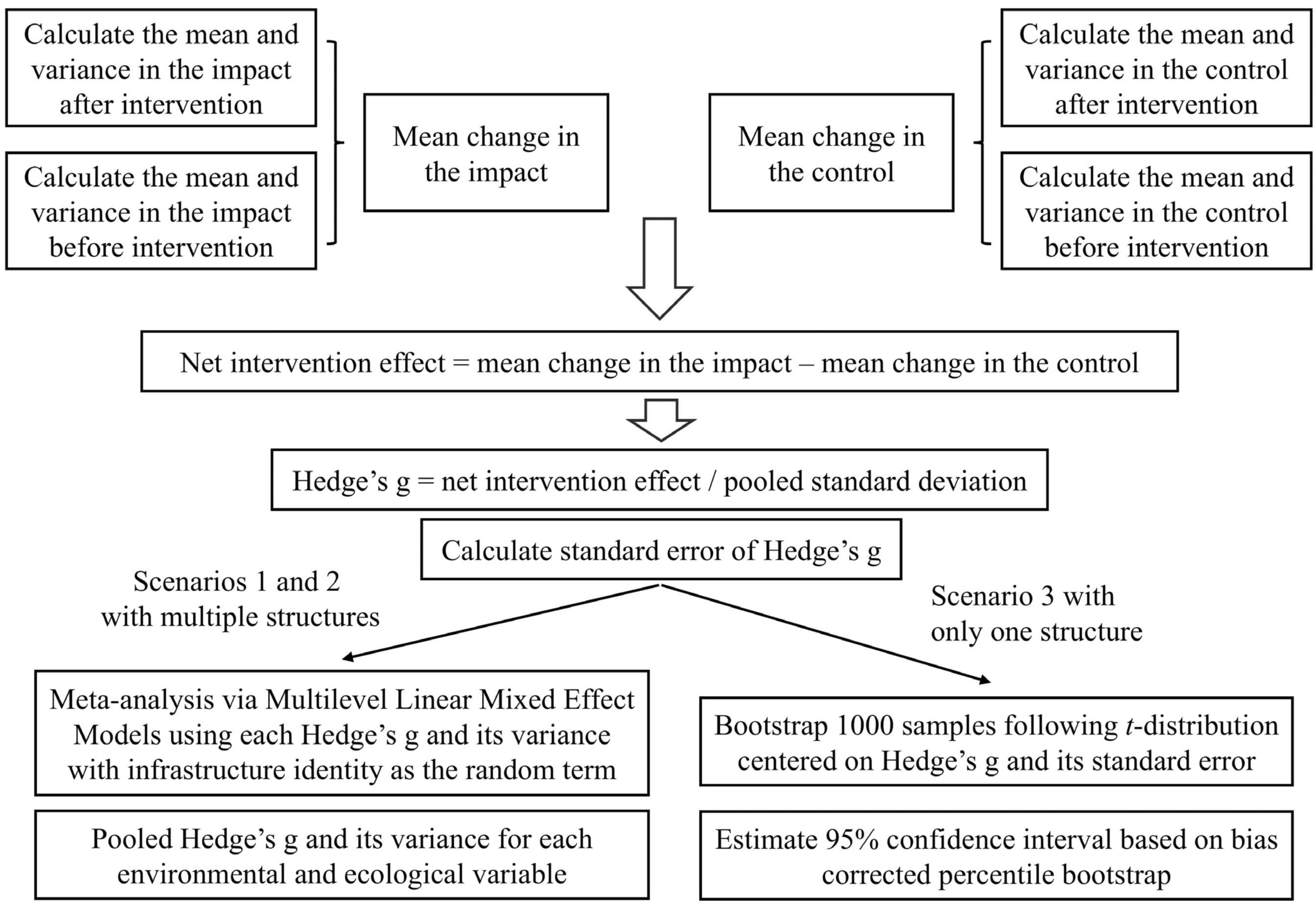


Fig. 2. Workflow illustrating how environmental and ecological data were processed and analyzed in the difference-in-differences framework to examine the overall decommissioning effects on each ecological metric.

$$Variance_{pooled} = \sqrt{\frac{(n_{i,b}-1)*S_{i,b}^2+(n_{i,a}-1)*S_{i,a}^2+(n_{c,b}-1)*S_{c,\ b}^2+(n_{c,a}-1)*S_{c,a}^2}{n_{i,b}+n_{i,af}+n_{c,b}+n_{c,i}-4}} \quad (3)$$

where $n_{i,b}$ and $s_{i,b}$ are sample size and variance of the impact before the intervention, $n_{i,a}$ and $s_{i,a}$ are sample size and variance of the impact after the intervention, $n_{c,b}$ and $s_{c,b}$ are sample size and variance of the control before the intervention, and $n_{c,a}$ and $s_{c,a}$ are sample size and variance of the control after the intervention.

The standard error (SE) of the Hedge's g effect size was calculated as follows:

$$SE_{hedge'sg} = \sqrt{\frac{(n_{i.b}+n_{i,a}+n_{c,b}+n_{c,a})}{(n_{i,b}+n_{i,a})*(n_{c,b}+n_{c,a})}+\frac{Hedge's\,g^2}{2*(n_{i.b}+n_{i,a}+n_{c,b}+n_{c,a})}} \quad (4)$$

We then simulated 1000 bias-corrected bootstrap samples to calculate the 95% confidence intervals (CIs) assuming a t-distribution centered on Hedge's g and its SE.

Statistical analysis

We applied this method to a consistent set of response variables at each scenario, including environmental variables, three alpha diversity metrics, mean individual body mass, and nine food web topological metrics. All analyses were conducted in R v4.4.1 (R Core Team 2025). For scenarios 1 and 2 with multiple structures, we used the "*metafor*" package to calculate pooled Hedge's g effect sizes and 95% CIs for each response variable using individual estimates at each structure (Viechtbauer 2010). For scenario 3 with only one structure, Hedge's g and its 95% CIs at each response variable were based on its net intervention effect. Multilevel linear mixed models were applied for scenarios 1 and 2, with the same variety of response variables as moderators and infrastructure identity as a random term. Test statistics and CIs for the fixed effects were computed using a t-distribution. Significance was determined when 95% CIs did not overlap with zero. The magnitude of Hedge's g effect sizes follows the thresholds: $|g| \leq 0.2$ (small); $|g| \leq 0.5$ (moderate); $|g| > 0.5$ (large) (Durlak 2009).

We used generalized linear latent variable models (GLLVMs) to examine changes in benthic community composition in the impact and control zones before and after decommissioning, and species-level responses to decommissioning effects in the three scenarios (Niku et al. 2019). We used the null model without predictors to compare with the treatment model with decommissioning effects as the predictor, represented by the interaction between status at sampling (before and after) and the distance-based treatment (impact and control). Each model used two latent variables to account for residuals beyond the predictors. Akaike Information Criterion (AIC) values were used in the model selection process to identify the optimal model distribution and structure. Species abundance data at each sampling site were then used to build a species abundance matrix, with rare species sampled at fewer than 5 sites excluded from the analysis (Zuur and Leno 2025). The species mean–variance relationship and Dunn–Smyth residual diagnostic plots showed a high proportion of zeros and overdispersion (Supporting Information Fig. S2), supporting the use of a negative binomial distribution as the best fit for our models.

Each GLLVM was used to examine species-level responses to the decommissioning effects. For each species, its estimated coefficient and 95% CIs were extracted to determine the directionality and magnitude of decommissioning effects on species abundance using the *coefplot* function. Species with significant coefficients (95% CIs excluding 0) were selected as potential bioindicators. The top three species with the largest positive and smallest negative coefficients were identified. We examined the community-level responses to the decommissioning effects using Permutational Multivariate ANOVA (PERMANOVA) instead of model-based ordination techniques in the GLLVM framework to accommodate small sample sizes in some treatments ($n < 10$) (Anderson 2001). The PERMANOVA provides a permutation-based approach to assess differences in community compositions across treatments. The multivariate homogeneity of group dispersions was used to analyze influences on group variances. As PERMANOVA is based on the Bray–Curtis dissimilarity matrix, we used the same dissimilarity matrix to visualize the results using Principal Coordinates Analysis (PCoA) (Abdi and Williams 2010).

Results

Chemical variables

In scenario 1, there were no significant effects of decommissioning on concentrations of either total hydrocarbons or heavy metals (Fig. 3). In scenario 2, post-decommissioning recovery had a significant and moderate negative effect on the concentration of total hydrocarbons (Hedge's $g = -0.44$; $p < 0.05$; Fig. 3), with a greater reduction in median concentration in the impact zone (from 1835 to 635 $\mu g\ g^{-1}$) than in the control zone (from 14 to 6 $\mu g\ g^{-1}$; Supporting Information Table S1). In scenario 3, decommissioning had a significant and large negative effect on concentrations of total hydrocarbons (Hedge's $g = -1.74$; $p < 0.001$; Fig. 3), with a reduction in median concentration in the impact zone (from 21,500 to 876 $\mu g\ g^{-1}$) and little change in the control zone (from 8.2 to 35 $\mu g\ g^{-1}$; Supporting Information Table S1). For individual metals, decommissioning in the long term had a significant and large positive effect on the concentration of total barium (Hedge's $g = 3.01$; $p < 0.001$; Supporting Information Fig. S4c), with a much greater increase in median concentration in the impact zone (from 3505 to 19,088 $\mu g\ g^{-1}$) than in the control zone (from 1352 to 4200 $\mu g\ g^{-1}$; Supporting

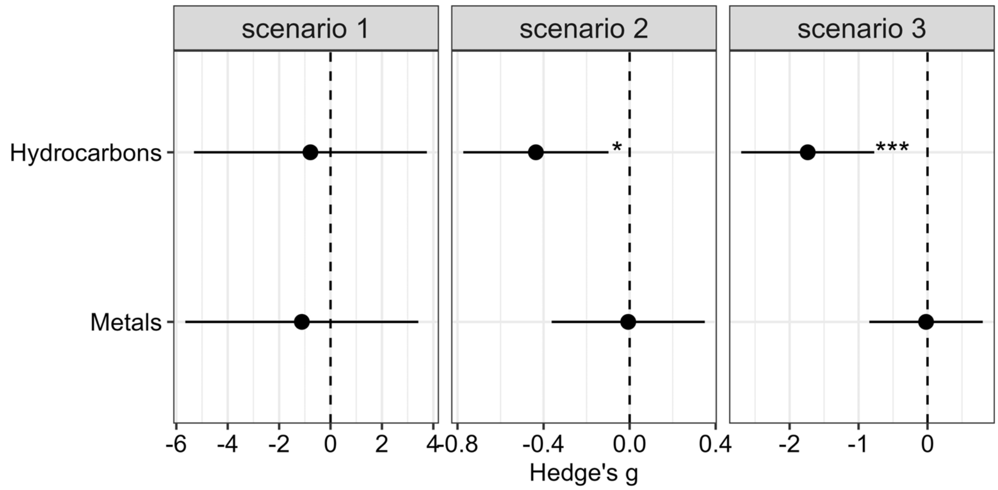


Fig. 3. The estimated pooled Hedge's *g* effect sizes and their 95% confidence intervals show the decommissioning effects on sediment concentrations of total hydrocarbons and metals for scenarios 1, 2, and 3. Statistically significant effects were marked with asterisks (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$).

Information Table S1). Decommissioning in scenario 3 had a significant and large negative effect on the concentration of copper (Hedge's $g = -0.99$; $p < 0.05$; Supporting Information Fig. S4c), with a reduction in the impact zone (from 43 to 24.4 μg g^{-1}) and little change in the control zone (from 3 to 4 μg g^{-1}; Supporting Information Table S1). Note that in comparison to the baseline at the pre-decommissioning levels, total hydrocarbons significantly declined in the long term after decommissioning (scenario 3), while there was no significant change in the short term after decommissioning (scenario 1). In comparison to the early time point post-decommissioning, total hydrocarbons significantly declined in the impact zone at the later time point post-decommissioning (scenario 2). There was no significant decline in the heavy metals for any of the three scenarios (Supporting Information Fig. S3).

Benthic biodiversity and composition

In scenario 1, decommissioning had a significant and large negative effect on total abundance (Hedge's $g = -0.74$; $p < 0.05$; Fig. 4a), with a smaller increase in the mean number of invertebrates in the impact zone (from 5728 to 10,427) than in the control zone (4388 to 11,808; Supporting Information Table S2). Decommissioning also had a significant and large negative effect on species richness (Hedge's $g = -0.90$; $p < 0.05$; Fig. 4a), with a reduction in the mean number of species in the impact zone (from 26 to 21) compared to an increase in the control zone (from 28 to 32; Supporting Information Table S2). In scenario 2, post-decommissioning recovery had a significant and large positive effect on total abundance (Hedge's $g = 0.53$; $p < 0.001$; Fig. 4b), with a smaller reduction in the mean number of invertebrates in the impact zone (from 23,835 to 16,134) than in the control zone (48,008 to 24,423; Supporting Information Table S2). In scenario 2, post-decommissioning recovery also had a significant and moderate negative effect on mean individual body mass (Hedge's $g = -0.39$; $p < 0.01$; Fig. 4b), with a greater reduction in mean body mass in the impact zone (from 0.119 to 0.100 g) than in the control zone (0.129–0.102; Supporting Information Table S2). In scenario 3, decommissioning had significant and large effects on total abundance (Hedge's $g = 1.84$; $p < 0.001$; Fig. 4c), species richness (Hedge's $g = 1.42$; $p < 0.01$; Fig. 4c), and Pielou's evenness (Hedge's $g = 0.97$; $p < 0.05$; Fig. 4c), with greater increases in all three metrics in the impact zone compared to the control (Supporting Information Table S2).

The decommissioning treatment in the GLLVM treatment model across three scenarios showed a substantially lower AIC value than the null treatment, indicating a significant decommissioning effect on community composition (Supporting Information Table S3). Consistent with this, PERMANOVA showed that decommissioning significantly altered benthic community composition across the four treatments, while the strength of differences varied across the scenarios (Supporting Information Table S4). Only scenario 3 showed a significant decline in the impact-control centroid distances after decommissioning, indicating a greater similarity of benthic communities between the impact and the control (Supporting Information Fig. S5). Instead, benthic communities in scenarios 1 and 2 exhibited weak distinctions across the four treatments, suggesting limited changes in community composition (Fig. 4d,e).

The GLLVM identified taxa that contributed the most to the observed community changes in each scenario (Supporting Information Fig. S6). In scenario 1, filter feeders (*Ditrupa arietina* and *Abra prismatica*) and grazers (*Echinocardium*) had the most negative responses to decommissioning effects. In scenario 2, some pollution-

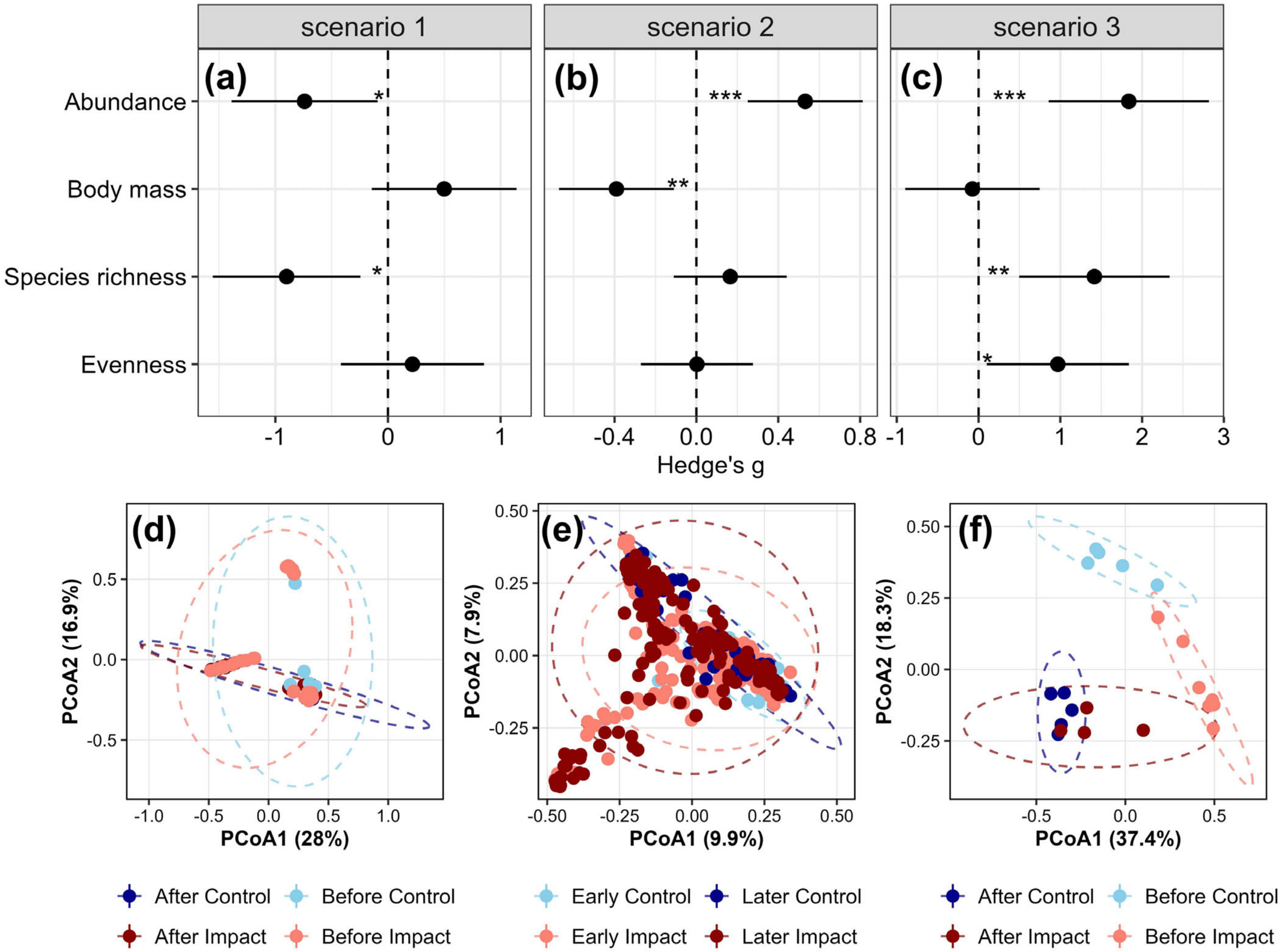


Fig. 4. (**a–c**) The estimated pooled Hedge's g effect size and their 95% confidence intervals show the decommissioning effects on benthic biodiversity for scenarios 1, 2, and 3. Statistically significant effects were marked with asterisks (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). (**d–f**) Ordinations of community composition across the four treatments for scenarios 1, 2, and 3.

intolerant detritivores including *Phascolion strombus* and *Thyasira sarsi* had positive responses to post-decommissioning recovery. In scenario 3, most of the taxa had negative responses to decommissioning effects including the pollution indicator *Capitella* spp. and the predatory worm *Harmothoe* sp. These findings align with the effect sizes of feeding group abundance and species richness, which experienced substantial changes after decommissioning and post-decommissioning recovery (Supporting Information Figs. S7, S8). In scenario 1, there was a significant and large negative effect of decommissioning on the abundance of filter feeders (Hedge's $g = -0.77$; $p < 0.05$), and grazers (Hedge's $g = -0.99$; $p < 0.05$). There was also a significant and large negative effect of decommissioning on the species richness of detritivores (Hedge's $g = -0.73$; $p < 0.05$), predators (Hedge's $g = -1.17$; $p < 0.01$), and scavengers (Hedge's $g = -0.99$; $p < 0.05$). In scenario 2, post-decommissioning recovery had a significant and positive effect on filter feeders (Hedge's $g = 0.43$; $p < 0.05$), detritivores (Hedge's $g = 0.71$; $p < 0.001$), and predators (Hedge's $g = 0.51$; $p < 0.01$). In scenario 3, decommissioning in the long term had significant and large positive effects on detritivores (Hedge's $g = 1.98$; $p < 0.001$), filter feeders (Hedge's $g = 1.51$; $p < 0.01$), and scavengers (Hedge's $g = 0.95$; $p < 0.05$).

Food web structure

In scenario 1, decommissioning had significant and large positive effects on the proportion of basal species (Hedge's $g = 0.73$; $p < 0.05$; Fig. 5a) and connectance (Hedge's $g = 0.82$; $p < 0.05$; Fig. 5a), but significant and large negative effects on mean trophic level (Hedge's $g = -0.77$; $p < 0.05$; Fig. 5a), link richness (Hedge's $g = -0.96$; $p < 0.01$; Fig. 5a), and linkage density (Hedge's $g = -0.71$; $p < 0.05$; Fig. 5a). In scenario 2, post-decommissioning recovery had significant and moderate positive effects on the proportion of intermediate species (Hedge's $g = 0.38$; $p < 0.01$; Fig. 5b) and linkage density

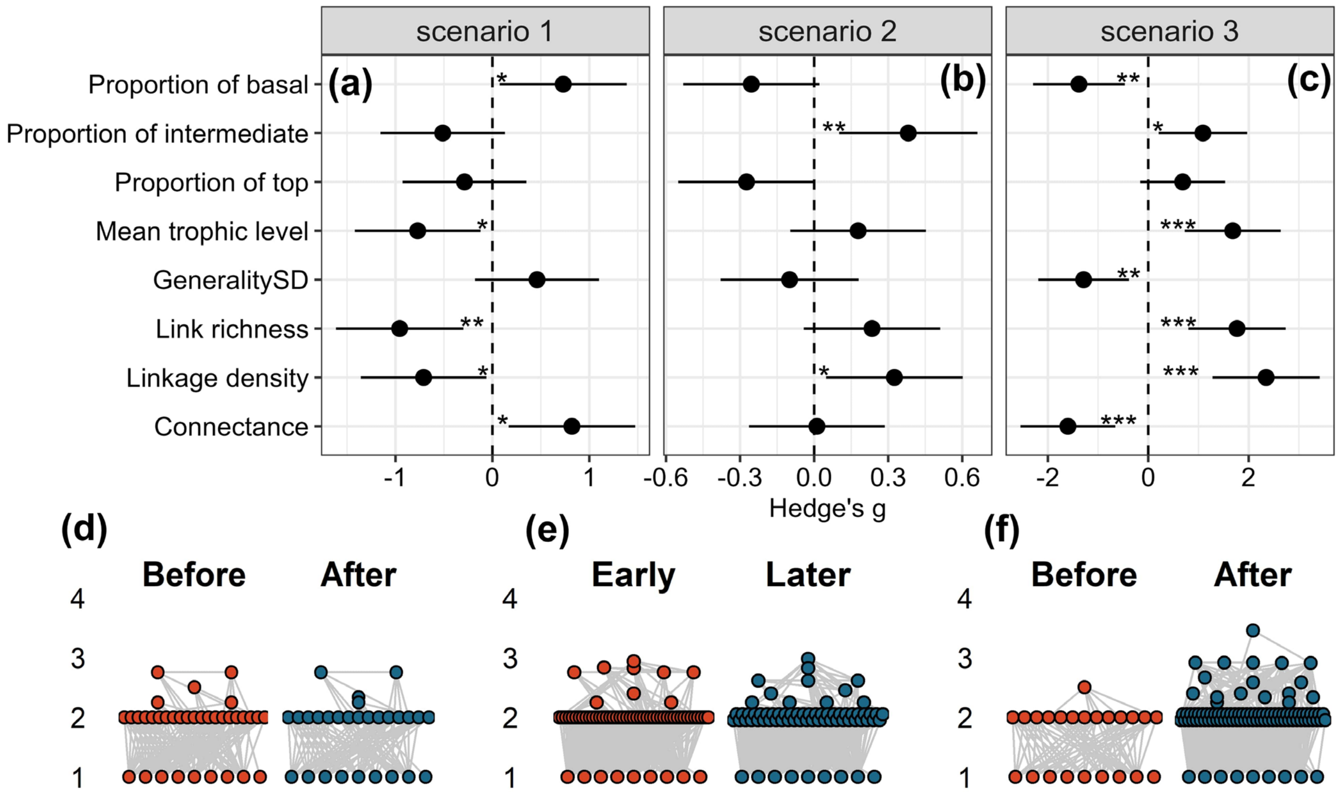


Fig. 5. (**a**–**c**) The estimated pooled Hedge's g effect sizes and their 95% confidence intervals show decommissioning effects on benthic food web topological properties. Examples are also given of a food web (**d**) before and after decommissioning in the short term, (**e**) in the early and later period of post-decommissioning recovery, and (**f**) before and after decommissioning in the long term. Circles are different taxa as nodes; gray lines are feeding interactions.

(Hedge's $g = 0.33$; $p < 0.05$; Fig. 5b). In scenario 3, decommissioning had significant and large positive effects on the proportion of intermediate species (Hedge's $g = 1.09$; $p < 0.05$; Fig. 5c), mean trophic level (Hedge's $g = 1.68$; $p < 0.001$; Fig. 5c), vulnerability (Hedge's $g = 1.32$; $p < 0.01$; Fig. 5c), link richness (Hedge's $g = 1.77$; $p < 0.001$; Fig. 5c), and linkage density (Hedge's $g = 2.35$; $p < 0.001$; Fig. 5c), but significant and large negative effects on the proportion of basal species (Hedge's $g = -1.38$; $p < 0.01$; Fig. 5c), generality (Hedge's $g = -1.29$; $p < 0.01$; Fig. 5c), and connectance (Hedge's $g = -1.60$; $p < 0.001$; Fig. 5c).

Discussion

Assessing potential environmental impacts and marine sensitivities near decommissioning activities is a regulatory requirement that provides essential environmental evidence to justify the chosen decommissioning option and supports risk-based approaches for post-decommissioning management (Department of Business Energy and Industrial Strategy 2018). Environmental assessments are usually proportionate to the scale of decommissioning activities on a case-by-case basis, but standardized regulated methods detailing the duration and frequency of monitoring plans are lacking, and this has contributed to an incomplete understanding of the likely responses of the soft sediment environment and benthic communities to O&G decommissioning. With limited long-term monitoring data, it is challenging for the current knowledge base to address whether and how the decommissioning of O&G infrastructure achieves environmental targets, for example, biodiversity net gains (Knights et al. 2024). Leveraging the best currently available industrial benthic monitoring database, this study found negative impacts of two fully decommissioned O&G structures within the first year, followed by a subtle recovery process after full decommissioning over 1–5 yr, and some positive effects of a partially removed structure in the longer term as a case study for the longer-term effects of decommissioning. Differences in the availability of before/after sampling, the extent of decommissioning, and the number of structures involved at each timescale make it difficult to disentangle the trajectory of recovery from potential confounding effects of the sampling design. Thus, our study also highlights the importance of gathering more environmental and ecological data around decommissioned O&G infrastructure to better understand potential impacts associated with the removal process and the long-term trajectory of recovery across different decommissioning options (e.g., partial or full removal). This is important to guide ecologically robust management strategies for future decommissioning practices.

Decommissioning effects on oil-associated contamination

The study found mixed results with regard to sediment contaminants. Specifically, there was a significant reduction in total hydrocarbon concentration in the post-decommissioning recovery (scenario 2) and long-term decommissioning (scenario 3), albeit with no significant change in some metal concentrations (i.e., zinc, lead, nickel) across all scenarios, which do not support the hypothesis of lower concentrations of all contaminants in the long term after decommissioning. The decline in total hydrocarbon concentration could be attributed to a number of factors, including the loss of low molecular weight compounds through volatilization (Chen et al. 2021), dispersion, emulsification, and solubilization in the water column (Zhao et al. 2015), and sinking to benthic sediments to biodegrade or become buried (Leahy and Colwell 1990; Xu et al. 2018). With the cessation of O&G production in the decommissioning phase, new hydrocarbon inputs from oil spills and waste discharges are no longer introduced, leaving the remaining residues to decline through a combination of physical transport, chemical dissolution, and biological degradation.

Many metals, on the other hand, appear to persist in the environment in the long term after decommissioning. For offshore sediments, metals are generally bound to mineral matrices and organic matter such as barite, bentonite, iron, and manganese oxides (de Azevedo et al. 2025). Without favorable physio-chemical conditions, these stable chemical forms reduce their bioavailability and solubility (Costa et al. 2023), while only a small labile and bioavailable fraction would disperse in the environment and interact with benthic detritivores and filter feeders (Yan and Wang 2002). The sediment quality guideline was used to assess the toxicity of hydrocarbons and metals present in the sediment (Long et al. 1995). Even in the long term of scenario 3, the median concentrations of lead and zinc were above the threshold values of the lower tenth percentile of concentration levels associated with adverse biological impacts (Supporting Information Table S1), which suggests potential environmental risks for benthic organisms and the environment. Barium, in the form of barite, is frequently used as a weighting material for drilling fluids and therefore has a substantial presence in the drill cuttings (Ellis et al. 2012). Even after cessation of production, barium (together with other metals including lead, zinc, and copper) may still have residual concentrations present near drilling sites (Olsgard and Gray 1995). This might be due to their adsorption to sediment particles or organic compounds near drilling sites, allowing them to accumulate in the benthic environment (Zhang et al. 2014).

Decommissioning effects on benthic biodiversity

Our results supported the hypothesis that total abundance and species richness increased in the long term after decommissioning, suggesting evidence of nature recovery. The results showed a complex response from adverse effects on species richness in the short term of two fully decommissioned structures, followed by a partial recovery in the medium term of post-decommissioning for multiple structures, to more diversified communities in the long term after decommissioning for a single structure as a case study (Fig. 4; Supporting Information Figs. S5, S9). The results are limited to the currently available structures in the specific context, calling for more data to identify generalized patterns. One possible explanation for negative impacts in the short term could be due to the debilitating nature of decommissioning activities (Odum et al. 1979). For example, dismantling of infrastructure components is likely to cause detrimental impacts to the surrounding benthic environment and organisms, for example, through resuspension of drill cuttings and other oil-associated contaminants from the sediment back into the water column and interacting directly with the seabed and organisms living on or in the sediments. In our case, benthic filter feeders and grazers were the groups that were most negatively affected (Supporting Information Fig. S7). In this period, ecosystems may experience further degradation rather than intermediate recovery following decommissioning (Rapport and Whitford 1999). In addition to that, decommissioning also alters the ecology of local ecosystems into which O&G infrastructure has become integrated (Spielmann et al. 2023). Removal of infrastructure is associated with the loss of epifaunal communities originally colonizing hard, complex substrates, alteration of local hydrodynamic regimes and sedimentary characteristics, and changes in contamination concentration in the surrounding sediment. The altered habitat baselines will have cascading effects on local seabed benthic invertebrates adapted to different resources and environmental conditions (Coates et al. 2014).

Contrasting ecological responses in benthic communities between the short and long term after decommissioning suggest temporal dependence of recovery in benthic communities. Yet, limited studies described the characteristics of benthic succession in the context of O&G decommissioning. Pearson and Rosenberg (1978) provided a useful framework to describe benthic recovery patterns in response to organic enrichment, showing an initial dominance of opportunistic organisms, followed by increasingly more diverse communities with greater fluctuations and progressing toward a state of equilibrium containing many more sensitive species. In our case, decommissioning also indicated the abatement of organic inputs, whereas there exists a variety of unique complexities that influence benthic successional trajectory and a novel state of equilibrium that is different from the pre-infrastructure one. These include the persistence of legacy contamination in the sediment (Woodward-Rowe et al. 2025), alteration of local hydrodynamics, hard substratum, and fouling communities associated with removal (Nicolette et al. 2023), and potential disturbances associated with the removal process (Fortune et al. 2024). These stressors associated with O&G decommissioning confound a predictable and gradual recovery process, which differs from previous recovery studies in dredging (Cooper et al. 2007) and trawling (Wang et al. 2021). Gade et al. (2024) found that redox-driven mineral weathering in cutting piles could enrich the surface sediment with metals despite its low lability state. During decommissioning, the disturbance-driven resuspension of weathered sediments could potentially increase the bioavailability of sequestered contaminants. This poses adverse impacts on marine benthos, explaining the further degradation in the short term before the ecosystem has fully recovered. Notably, a significant reduction in mean body mass in the impact zone post-decommissioning recovery suggests that initial colonizers tend to be small opportunists with rapid reproduction and a short life span (Ryu et al. 2011), with larger organisms only establishing in the longer term (Rosenberg 2001). Henry et al. (2017) found that benthic recovery after the cessation of drilling in the northern North Sea required over 6.8 yr, while recovery in the central North Sea took over 8 yr.

Partial recovery was detected in the long term after decommissioning, with a significant increase in both total abundance and species richness in the impact zone (Fig. 4). Changes in benthic community composition were most stark in scenario 3, whereby impact and control communities were homogenized following decommissioning, with no significant difference in beta diversity (Supporting Information Fig. S9). The opportunistic polychaete *Capitella* spp. was the most abundant species in the impact zone before decommissioning, which are typical pollution bioindicators in organic-enriched and disturbed environments (Tomassetti et al. 2016). Communities in scenario 3 became more diverse with the colonization of more pollution-sensitive species, including the brittle stars *T. sarsi* and *P. strombus* and the heart urchin *Echinocardium cordatum* (Supporting Information Fig. S6), reflecting improved benthic habitat quality (Borja et al. 2000; Rosenberg et al. 2002). The positive responses of many pollution-intolerant taxa, including *T. sarsi* and *P. strombus*, in the post-decommissioning recovery of scenario 2 were consistent with an improving environment. Our results align with previous assessments showing a decrease in polychaetes and a concurrent increase in pollution-intolerant taxa after decommissioning (OSPAR Commission 2019). This highlights the potential for the recovery of benthic communities after decommissioning, albeit only at a single O&G structure due to the absence of long-term monitoring in current industry datasets. It should also be noted that observed benthic recovery in scenario 3 is relative to its ecological state prior to decommissioning, given the pre-construction baseline data are not available, highlighting a gap in industry data collection. Thus, the baseline for scenario 3 was already in an ecologically stressed condition, but lacking the pre-construction baseline, we still found increased biodiversity and food web complexity and, therefore, improved community status. The recovery is therefore not a simple return to a "pristine" pre-construction state but rather depends on local environmental conditions evident in the control treatment. Time-series analysis shows a non-linear complex process for benthic communities to approach a new equilibrium by adjusting to new resources and environmental conditions (Supporting Information Figs. S10, S11).

Reorganization of trophic architecture: Gains or losses?

The significant increase in link richness, linkage density, and mean trophic level supported our hypothesis of greater food web complexity in the long term after decommissioning (Fig. 5). The significant decrease in connectance and generality seems counterintuitive at first glance, but actually indicates a greater proportion of specialist consumers in the food web. Since less connected dietary specialists are more prone to extinction and dietary generalists are more likely to thrive under environmentally stressful conditions (Laske et al. 2018), the decreasing connectance and generality in the long term after decommissioning suggest an improved environment that can cater to a wider range of trophic niches. The improved communities were also consistent with a more diversified community composition with increased abundance across feeding groups in the impact zone after decommissioning (Supporting Information Fig. S7). The increase in vulnerability also indicates a greater number of predators in the community, which is consistent with the higher mean trophic level. The increase in link richness and linkage density demonstrates increased energy availability and more redundancy in energy flow (Scotti et al. 2009). Nevertheless, the decrease in connectance may be associated with reduced resilience to disturbances through an increased risk of secondary extinctions or invasions (Dunne et al. 2002b). However, the paucity of available data for fully decommissioned structures makes it difficult to ascribe beneficial effects on long timescales given the partial removal used in this scenario, which contrasts with the full removal in scenarios 1 and 2. Therefore, it is unclear if the beneficial effects on diversity and food webs in scenario 3 are down to the longer timescale allowed for recovery, or the lower initial disturbance to the surrounding sediment from leaving the footings of the decommissioned platform in place. Future studies are encouraged to examine how different decommissioning options affect ecological responses in the long term.

In the short term after decommissioning, completely opposing patterns to the long-term recovery were found, with a significant increase in the proportion of basal species and connectance, and a significant decrease in mean trophic level, link richness, and linkage density (Fig. 5). The reduction in mean trophic level indicates a greater dominance of basal species, which suggests inadequate resources to support energy transfer to higher trophic levels (Kaunzinger and Morin 1998). The decrease in the number and density of food web interactions reconciles with the loss of species richness, which leads to lower trophic redundancy. Higher connectance suggests increased resilience against disturbances (Dunne et al. 2002a), however, whereby a simplified but more tightly connected food web may act as a stabilizing mechanism that prevents communities from experiencing secondary extinctions following a perturbation (Nordström and Bonsdorff 2017), which is also a typical manifestation in a stressed ecosystem (Nagelkerken et al. 2020). Despite the lack of pre-infrastructure surveys to inform baseline conditions at the structures, the trajectory of benthic recovery was found with positive effects on the proportion of intermediate species and linkage density (Fig. 5). However, the lack of significant distinction in community compositions suggests that benthic recovery is relatively subtle in the 1–5 yr timeframe (Fig. 4).

Recommendations for monitoring of decommissioning

The preparation and implementation of decommissioning in the North Sea is a lengthy regulatory process that requires environmental appraisals to support proposed decommissioning options and their potential impacts on the marine environment. Environmental surveys are needed to fulfill regulatory requirements, provide an evidence base prior to cessation of production for potential impacts and their consequences to the environment, and to justify the chosen option having minimal environmental impacts (Department of Business Energy and Industrial Strategy 2018). Currently, there is no statutory requirement specifying the implementation of long-term monitoring and recommended frequency of key time points, which means there is a lack of consistent environmental and ecological data for monitoring the impacts of decommissioning on marine ecosystems. Using survey data before and after decommissioning at different temporal scales, we attempted to show a variability in benthic diversity and food web responses. To better accommodate the needs of investigating long-term decommissioning effects, we propose the following recommendations concerning (i) the prioritization of monitoring long-term decommissioning consequences; (ii) a standardized data workflow to integrate with available databases, and (iii) enhanced stakeholder participation in the decommissioning decision-making and accessibility and transparency of monitoring data.

i. The absence of continuous long-term monitoring surveys post-decommissioning made it difficult to implement a trend-based approach to understand the trajectory of benthic recovery at different successional stages. Our results found that negative effects on benthic biodiversity and food webs persisted in the short timescale (within 12 months), followed by signals of recovery in the medium (1–5 yr) and long term (over 5 yr). This illustrates how future post-decommissioning sampling strategies should account for monitoring at key timepoints (e.g., within 12 months, then after 2, 3, 5, and 10 yr) to provide an adequate temporal range to detect the potential environmental and ecological consequences of decommissioning.

ii. Standardization in the sampling protocol would be beneficial not only to the comparative analysis between historical baseline data with planned monitoring, but also to allow the integration of existing surveys beyond the industrial sector, including government agencies and research institutions. The methodologies and principles established by existing standardized benthic sampling protocols, for example, the regional seabed monitoring program developed by Cooper and Barry (2017), could be further improved by accounting for the uniqueness and difficulties of sampling O&G infrastructure. For example, the distinction of sampling should consider different operational phases of O&G infrastructure, including baseline sampling prior to exploitation, sampling during the operational stage, and post-decommissioning sampling. Important factors should be recorded at each sampling location, such as the transect, angle in direction, and water depth. It would be beneficial to establish an integrated framework to unify the efforts of industry, research institutions, and government to participate in benthic monitoring, which would improve knowledge and decision-making around decommissioning.

iii. It is essential to collect environmental and ecological information to identify the optimal decommissioning scenario that brings environmental and societal gains. Without the evidence, there is a risk that the substantial costs in decommissioning do not yield desirable outcomes for the industry and the public. There is also a need for improving data transparency of environmental appraisals submitted for decommissioning approvals, as these assessments tend to be summarized in reports, with raw survey data remaining inaccessible, particularly for decommissioned O&G infrastructure. The UK Benthos database offers valuable historical data to understand the impacts of offshore hydrocarbon exploitation. However, a lack of post-decommissioning data constrains the ability to compare benthic conditions before and after decommissioning, as well as to evaluate post-decommissioning recovery relative to baseline conditions prior to hydrocarbon exploitation. Our scenario-based approach requires comprehensive and long-term benthic monitoring to validate the trajectory of post-decommissioning recovery of benthic communities.

Conclusion

This study reveals environmental and ecological impacts of O&G decommissioning on marine ecosystems. Hydrocarbons, especially those with lower molecular weight, degrade relatively rapidly after decommissioning, while heavy metals may persist longer in the sediment at levels that could impact benthic organisms. There were detrimental impacts of decommissioning in the short term, with a loss of species richness and simplified food webs. Increases in the proportion of intermediate species and linkage density in the medium-term post-decommissioning suggest some recovery is happening, but community composition exhibits greater inertia over this timescale. The greater food web complexity in the long term after decommissioning indicated longer pathways of energy flux and more trophic redundancy in the face of further perturbations, with impact zone communities sharing a similar composition to those of background controls. Given that the data underpinning our findings are limited to scenarios with different structures and decommissioning options, the study highlights the critical need for more systematic long-term monitoring of O&G decommissioning to better inform future practices.

Author Contributions

Zelin Chen: Writing – review and editing, writing – original draft, visualization, methodology, formal analysis, data curation, conceptualization. **Tom C. Cameron:** Writing – review and editing, supervision. **Elena Couce:** Writing – review and editing, supervision, methodology. **Clement Garcia:** Writing – review and editing, resources, data curation. **Natalie Hicks:** Writing – review and editing, supervision, project administration, funding acquisition, data curation. **Gareth E. Thomas:** Writing – review and editing, methodology, data curation, conceptualization. **Murray S. A. Thompson:** Writing – review and editing, supervision, methodology, formal analysis. **Corinne Whitby:** Writing – review and editing, supervision, project administration, funding acquisition. **Eoin J. O'Gorman:** Writing – review and editing, supervision, funding acquisition, formal analysis, data curation, conceptualization.

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Conflicts of Interest

None declared.

Data Availability Statement

The R scripts and data that support the findings of this study are available from the University of Essex Research Data Repository at https://doi.org/10.5526/ERDR-00000229.

References

Abdi, H., and L. J. Williams. 2010. "Principal Component Analysis." *Wiley Interdisciplinary Reviews: Computational Statistics* 2: 433–459. https://doi.org/10.1002/wics.101.

Altin, D., T. K. Frost, and I. Nilssen. 2009. "Approaches for Derivation of Environmental Quality Criteria for Substances Applied in Risk Assessment of Discharges From Offshore Drilling Operations." *Integrated Environmental Assessment and Management* 4: 204–214. https://doi.org/10.1897/IEAM_2007-045.

Anderson, M. J. 2001. "A New Method for Non-Parametric Multivariate Analysis of Variance." *Austral Ecology* 26: 32–46. https://doi.org/10.1111/j.1442-9993.2001.01070.pp.x.

Bakke, T., J. Klungsoyr, and S. Sanni. 2013. "Environmental Impacts of Produced Water and Drilling Waste Discharges From the Norwegian Offshore Petroleum Industry." *Marine Environmental Research* 92: 154–169. https://doi.org/10.1016/j.marenvres.2013.09.012.

Borja, A., J. Franco, and V. Pérez. 2000. "A Marine Biotic Index to Establish the Ecological Quality of Soft-Bottom Benthos Within European Estuarine and Coastal Environments." *Marine Pollution Bulletin* 40: 1100–1114. https://doi.org/10.1016/S0025-326X(00)00061-8.

Burdon, D., S. Barnard, S. J. Boyes, and M. Elliott. 2018. "Oil and Gas Infrastructure Decommissioning in Marine Protected Areas: System Complexity, Analysis and Challenges." *Marine Pollution Bulletin* 135: 739–758. https://doi.org/10.1016/j.marpolbul.2018.07.077.

Chen, A., X. Wu, S. L. M. Simonich, H. Kang, and Z. Xie. 2021. "Volatilization of Polycyclic Aromatic Hydrocarbons (PAHs) Over the North Pacific and Adjacent Arctic Ocean: The Impact of Offshore Oil Drilling." *Environmental Pollution* 268: 115963. https://doi.org/10.1016/j.envpol.2020.115963.

Chen, Z., T. C. Cameron, E. Couce, et al. 2024. "Oil and Gas Platforms Degrade Benthic Invertebrate Diversity and Food Web Structure." *Science of the Total Environment* 929: 172536. https://doi.org/10.1016/j.scitotenv.2024.172536.

Clare, D. S., S. G. Bolam, P. S. O. McIlwaine, C. Garcia, J. M. Murray, and J. D. Eggleton. 2022. "Biological Traits of Marine Benthic Invertebrates in Northwest Europe." *Sci Data* 9: 339. https://doi.org/10.1038/s41597-022-01442-y.

Coates, D. A., Y. Deschutter, M. Vincx, and J. Vanaverbeke. 2014. "Enrichment and Shifts in Macrobenthic Assemblages in an Offshore Wind Farm Area in the Belgian Part of the North Sea." *Marine Environmental Research* 95: 1–12. https://doi.org/10.1016/j.marenvres.2013.12.008.

Cohen, J. 2013. Statistical Power Analysis for the Behavioral Sciences. Routledge. https://doi.org/10.4324/9780203771587.

Coolen, J. W. P., J. Vanaverbeke, J. Dannheim, et al. 2022. "Generalized Changes of Benthic Communities After Construction of Wind Farms in the Southern North Sea." *Journal of Environmental Management* 315: 115173. https://doi.org/10.1016/j.jenvman.2022.115173.

Cooper, K., and J. Barry. 2017. "A Big Data Approach to Macrofaunal Baseline Assessment, Monitoring and Sustainable Exploitation of the Seabed." *Scientific Reports* 7: 12431. https://doi.org/10.1038/s41598-017-11377-9.

Cooper, K., S. Boyd, J. Eggleton, D. Limpenny, H. Rees, and K. Vanstaen. 2007. "Recovery of the Seabed Following Marine Aggregate Dredging on the Hastings Shingle Bank Off the Southeast Coast of England." *Estuarine, Coastal and Shelf Science* 75: 547–558. https://doi.org/10.1016/j.ecss.2007.06.004.

Costa, L., L. C. Costa, C. F. Carvalho, et al. 2023. "Physical and Chemical Characterization of Drill Cuttings: A Review." *Marine Pollution Bulletin* 194: 115342. https://doi.org/10.1016/j.marpolbul.2023.115342.

de Azevedo, P. C. d. C., P. C. Costa Azevedo, S. R. Krzyzaniak, et al. 2025. "Chemical Fractionation and Risk Assessment of Metals in Drill Cuttings From Onshore and Offshore Oil and Gas Wells." *Marine Pollution Bulletin* 213: 117635. https://doi.org/10.1016/j.marpolbul.2025.117635.

Dell'Anno, F., E. Rastelli, C. Sansone, C. Brunet, A. Ianora, and A. Dell'Anno. 2021. "Bacteria, Fungi and Microalgae for the Bioremediation of Marine Sediments Contaminated by Petroleum Hydrocarbons in the Omics Era." *Microorganisms* 9: 1695. https://doi.org/10.3390/microorganisms9081695.

Department of Business Energy and Industrial Strategy. 2018. Guidance Notes: Decommissioning of Offshore Oil and Gas Installations and Pipelines. Offshore Petroleum Regulator for Environment and Decommissioning.

Dunne, J. A., R. J. Williams, and N. D. Martinez. 2002*a*. "Food-Web Structure and Network Theory: The Role of Connectance and Size." *Proceedings of the National Academy of Sciences of the United States of America* 99: 12917–12922. https://doi.org/10.1073/pnas.192407699.

Dunne, J. A., R. J. Williams, and N. D. Martinez. 2002*b*. "Network Structure and Biodiversity Loss in Food Webs: Robustness Increases With Connectance." *Ecology Letters* 5: 558–567. https://doi.org/10.1046/j.1461-0248.2002.00354.x.

Durlak, J. A. 2009. "How to Select, Calculate, and Interpret Effect Sizes." *Journal of Pediatric Psychology* 34: 917–928. https://doi.org/10.1093/jpepsy/jsp004.

Ellis, J., G. Fraser, and J. Russell. 2012. "Discharged Drilling Waste From Oil and Gas Platforms and Its Effects on Benthic Communities." *Marine Ecology Progress Series* 456: 285–302. https://doi.org/10.3354/meps09622.

Fam, M. L., D. Konovessis, L. S. Ong, and H. K. Tan. 2018. "A Review of Offshore Decommissioning Regulations in Five Countries—Strengths and Weaknesses." *Ocean Engineering* 160: 244–263. https://doi.org/10.1016/j.oceaneng.2018.04.001.

Fortune, I., and D. Paterson. 2018. "Ecological Best Practice in Decommissioning: A Review of Scientific Research." *ICES Journal of Marine Science* 77: 1079–1091. https://doi.org/10.1093/icesjms/fsy130.

Fortune, I. S., A. S. Madgett, A. Scarborough Bull, N. Hicks, M. S. Love, and D. M. Paterson. 2024. "Haven or Hell? A Perspective on the Ecology of Offshore Oil and Gas Platforms." *PLOS Sustainability and Transformation* 3: e0000104. https://doi.org/10.1371/journal.pstr.0000104.

Fowler, A. M., A.-M. Jørgensen, J. W. P. Coolen, et al. 2020. "The Ecology of Infrastructure Decommissioning in the North Sea: What We Need to Know and How to Achieve It." *ICES Journal of Marine Science* 77: 1109–1126. https://doi.org/10.1093/icesjms/fsz143.

Fujii, T. 2015. "Temporal Variation in Environmental Conditions and the Structure of Fish Assemblages around an Offshore Oil Platform in the North Sea." *Marine Environmental Research* 108: 69–82. https://doi.org/10.1016/j.marenvres.2015.03.013.

Gade, C., R. von Hellfeld, L. Mbadugha, and G. Paton. 2024. "Mercury Fingerprint: A Comparative Evaluation of Lability in North Sea Drill Cuttings." *Marine Pollution Bulletin* 204: 116518. https://doi.org/10.1016/j.marpolbul.2024.116518.

Gates, A. R., and D. O. Jones. 2012. "Recovery of Benthic Megafauna From Anthropogenic Disturbance at a Hydrocarbon Drilling Well (380 m Depth in the Norwegian Sea)." *PLoS One* 7: e44114. https://doi.org/10.1371/journal.pone.0044114.

Henry, L. A., D. Harries, P. Kingston, and J. M. Roberts. 2017. "Historic Scale and Persistence of Drill Cuttings Impacts on North Sea Benthos." *Marine Environmental Research* 129: 219–228. https://doi.org/10.1016/j.marenvres.2017.05.008.

Hudson, L. N., R. Emerson, G. B. Jenkins, et al. 2013. "Cheddar: Analysis and Visualisation of Ecological Communities in R." *Methods in Ecology and Evolution* 4: 99–104. https://doi.org/10.1111/2041-210X.12005.

Kaunzinger, C. M., and P. J. Morin. 1998. "Productivity Controls Food-Chain Properties in Microbial Communities." *Nature* 395: 495–497. https://doi.org/10.1038/26741.

Knights, A. M., A. J. Lemasson, L. B. Firth, et al. 2024. "To What Extent Can Decommissioning Options for Marine Artificial Structures Move Us Toward Environmental Targets?" *Journal of Environmental Management* 350: 119644. https://doi.org/10.1016/j.jenvman.2023.119644.

Lakhal, S. Y., M. Khan, and M. R. Islam. 2009. "An 'Olympic' Framework for a Green Decommissioning of an Offshore Oil Platform." *Ocean and Coastal Management* 52: 113–123. https://doi.org/10.1016/j.ocecoaman.2008.10.007.

Laske, S. M., A. E. Rosenberger, M. S. Wipfli, and C. E. Zimmerman. 2018. "Generalist Feeding Strategies in Arctic Freshwater Fish: A Mechanism for Dealing With Extreme Environments." *Ecology of Freshwater Fish* 27: 767–784. https://doi.org/10.1111/eff.12391.

Leahy, J. G., and R. R. Colwell. 1990. "Microbial Degradation of Hydrocarbons in the Environment." *Microbiological Reviews* 54: 305–315. https://doi.org/10.1128/mr.54.3.305-315.1990.

Long, E. R., D. D. Macdonald, S. L. Smith, and F. D. Calder. 1995. "Incidence of Adverse Biological Effects Within Ranges of Chemical Concentrations in Marine and Estuarine Sediments." *Environmental Management* 19: 81–97. https://doi.org/10.1007/BF02472006.

MacIntosh, A., K. Dafforn, B. Penrose, A. Chariton, and T. Cresswell. 2021. "Ecotoxicological Effects of Decommissioning Offshore Petroleum Infrastructure: A Systematic Review." *Critical Reviews in Environmental Science and Technology* 52: 3283–3321. https://doi.org/10.1080/10643389.2021.1917949.

Marappan, S., R. Stokke, M. P. Malinovsky, and A. Taylor. 2022. "Assessment of Impacts of the Offshore Oil and Gas Industry on the Marine Environment." In OSPAR 2023: The 2023 Quality Status Report for the North-East Atlantic. OSPAR Commission.

Martins, M. C. I., M. I. Carter, S. Rouse, and D. J. Russell. 2023. "Offshore Energy Structures in the North Sea: Past, Present and Future." *Marine Policy* 152: 105629. https://doi.org/10.1016/j.marpol.2023.105629.

Melbourne-Thomas, J., K. R. Hayes, A. J. Hobday, et al. 2021. "Decommissioning Research Needs for Offshore Oil and Gas Infrastructure in Australia." *Frontiers in Marine Science* 8: 1007. https://doi.org/10.3389/fmars.2021.711151.

Nagelkerken, I., S. U. Goldenberg, C. M. Ferreira, H. Ullah, and S. D. Connell. 2020. "Trophic Pyramids Reorganize When Food Web Architecture Fails to Adjust to Ocean Change." *Science* 369: 829–832. https://doi.org/10.1126/science.aax0621.

Neff, J., K. Lee, and E. M. DeBlois. 2011. Produced Water: Overview of Composition, Fates, and Effects. Produced Water: Environmental Risks and Advances in Mitigation Technologies, 3–54. Springer.

Nicolette, J. P., N. A. Nelson, M. K. Rockel, et al. 2023. "A Framework for a Net Environmental Benefit Analysis Based Comparative Assessment of Decommissioning Options for Anthropogenic Subsea Structures: A North Sea Case Study." *Frontiers in Marine Science* 9: 1020334. https://doi.org/10.3389/fmars.2022.1020334.

Niku, J., F. K. C. Hui, S. Taskinen, D. I. Warton, and S. Goslee. 2019. "Gllvm: Fast Analysis of Multivariate Abundance Data With Generalized Linear Latent Variable Models in r." *Methods in Ecology and Evolution* 10: 2173–2182. https://doi.org/10.1111/2041-210X.13303.

Nordström, M. C., and E. Bonsdorff. 2017. "Organic Enrichment Simplifies Marine Benthic Food Web Structure." *Limnology and Oceanography* 62: 2179–2188. https://doi.org/10.1002/lno.10558.

North Sea Transition Authority. 2024. UKCS Offshore Activity. https://www.nstauthority.co.uk/. https://doi.org/10.13104/imri.2024.0009.

Odum, E. P., J. T. Finn, and E. H. Franz. 1979. "Perturbation Theory and the Subsidy-Stress Gradient." *Bioscience* 29: 349–352. https://doi.org/10.2307/1307690.

Offshore Energies UK. 2015. UK Benthos Database 5.17. https://oeuk.org.uk/.

O'Gorman, E. J., O. L. Petchey, K. J. Faulkner, et al. 2019. "A Simple Model Predicts How Warming Simplifies Wild Food Webs." *Nature Climate Change* 9: 611–616. https://doi.org/10.1038/s41558-019-0513-x.

Olsgard, F., and J. S. Gray. 1995. "A Comprehensive Analysis of the Effects of Offshore Oil and Gas Exploration and Production on the Benthic Communities of the Norwegian Continental Shelf." *Marine Ecology Progress Series* 122: 277–306. https://doi.org/10.3354/meps122277.

OSPAR Commission. 2019. Assessment of the Disturbance of Drill Cuttings During Decommissioning. OSPAR Commission.

Parente, V., D. Ferreira, E. Moutinho dos Santos, and E. Luczynski. 2006. "Offshore Decommissioning Issues: Deductibility and Transferability." *Energy Policy* 34: 1992–2001. https://doi.org/10.1016/j.enpol.2005.02.008.

Pearson, T., and R. Rosenberg. 1978. "Macrobenthic Succession in Relation to Organic Enrichment and Pollution of the Marine Environment." *Oceanography and Marine Biology: An Annual Review* 16: 229–311. https://doi.org/10.2983/035.034.0121U1.10.

R Core Team. 2025. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rapport, D. J., and W. G. Whitford. 1999. "How Ecosystems Respond to Stress: Common Properties of Arid and Aquatic Systems." *Bioscience* 49: 193–203. https://doi.org/10.2307/1313509.

Rosenberg, R. 2001. "Marine Benthic Faunal Successional Stages and Related Sedimentary Activity." *Scientia Marina* 65: 107–119. https://doi.org/10.3989/scimar.2001.65s2107.

Rosenberg, R., S. Agrenius, B. Hellman, H. C. Nilsson, and K. Norling. 2002. "Recovery of Marine Benthic Habitats and Fauna in a Swedish Fjord Following Improved Oxygen Conditions." *Marine Ecology Progress Series* 234: 43–53. https://doi.org/10.3354/meps234043.

Russell, D. J., D. J. F. Russell, S. M. J. M. Brasseur, et al. 2014. "Marine Mammals Trace Anthropogenic Structures at Sea." *Current Biology* 24: R638–R639. https://doi.org/10.1016/j.cub.2014.06.033.

Ryu, J., J. S. Khim, S.-G. Kang, D. Kang, C.-h. Lee, and C.-h. Koh. 2011. "The Impact of Heavy Metal Pollution Gradients in Sediments on Benthic Macrofauna at Population and Community Levels." *Environmental Pollution* 159: 2622–2629. https://doi.org/10.1016/j.envpol.2011.05.034.

Schroeder, D. M., and M. S. Love. 2004. "Ecological and Political Issues Surrounding Decommissioning of Offshore Oil Facilities in the Southern California Bight." *Ocean and Coastal Management* 47: 21–48. https://doi.org/10.1016/j.ocecoaman.2004.03.002.

Scotti, M., C. Bondavalli, and A. Bodini. 2009. "Linking Trophic Positions and Flow Structure Constraints in Ecological Networks: Energy Transfer Efficiency or Topology Effect?"

Ecological Modelling 220: 3070–3080. https://doi.org/10.1016/j.ecolmodel.2008.07.034.

Spielmann, V., J. Dannheim, T. Brey, and J. W. P. Coolen. 2023. "Decommissioning of Offshore Wind Farms and Its Impact on Benthic Ecology." *Journal of Environmental Management* 347: 119022. https://doi.org/10.1016/j.jenvman.2023.119022.

Tomassetti, P., P. Gennaro, L. Lattanzi, et al. 2016. "Benthic Community Response to Sediment Organic Enrichment by Mediterranean Fish Farms: Case Studies." *Aquaculture* 450: 262–272. https://doi.org/10.1016/j.aquaculture.2015.07.019.

van der Molen, J., L. M. García-García, P. Whomersley, A. Callaway, P. E. Posen, and K. Hyder. 2018. "Connectivity of Larval Stages of Sedentary Marine Communities Between Hard Substrates and Offshore Structures in the North Sea." *Scientific Reports* 8: 1–14. https://doi.org/10.1038/s41598-018-32912-2.

van der Stap, T., J. W. Coolen, and H. J. Lindeboom. 2016. "Marine Fouling Assemblages on Offshore Gas Platforms in the Southern North Sea: Effects of Depth and Distance From Shore on Biodiversity." *PLoS One* 11: e0146324. https://doi.org/10.1371/journal.pone.0146324.

Viechtbauer, W. 2010. "Conducting Meta-Analyses in R With the metafor Package." *Journal of Statistical Software* 36: 1–48. https://doi.org/10.18637/jss.v036.i03.

Wang, Z., K. M. Leung, Y.-H. Sung, D. Dudgeon, and J.-W. Qiu. 2021. "Recovery of Tropical Marine Benthos After a Trawl Ban Demonstrates Linkage Between Abiotic and Biotic Changes." *Communications Biology* 4: 212. https://doi.org/10.1038/s42003-021-01732-y.

Wing, C., K. Simon, and R. A. Bello-Gomez. 2018. "Designing Difference in Difference Studies: Best Practices for Public Health Policy Research." *Annual Review of Public Health* 39: 453–469. https://doi.org/10.1146/annurev-publhealth-040617-013507.

Woodward-Rowe, H., F. Dal Molin, B. H. Gregson, C. Mason, R. Parker, and N. Hicks. 2025. "Sedimentary Blue Carbon around Decommissioned Oil and Gas Platforms in the North Sea." *Marine Pollution Bulletin* 219: 118250. https://doi.org/10.1016/j.marpolbul.2025.118250.

WoRMS Editorial Board. 2023. World Register of Marine Species. https://www.marinespecies.org at VLIZ.

Xu, X., W. Liu, S. Tian, et al. 2018. "Petroleum Hydrocarbon-Degrading Bacteria for the Remediation of Oil Pollution under Aerobic Conditions: A Perspective Analysis." *Frontiers in Microbiology* 9: 2885. https://doi.org/10.3389/fmicb.2018.02885.

Yan, Q.-L., and W.-X. Wang. 2002. "Metal Exposure and Bioavailability to a Marine Deposit-Feeding Sipuncula, *Sipunculus nudus*." *Environmental Science & Technology* 36: 40–47. https://doi.org/10.1021/es015604x.

Zhang, C., Z.-g. Yu, G.-m. Zeng, et al. 2014. "Effects of Sediment Geochemical Properties on Heavy Metal Bioavailability." *Environment International* 73: 270–281. https://doi.org/10.1016/j.envint.2014.08.010.

Zhao, X., Y. Gong, S. E. O'Reilly, and D. Zhao. 2015. "Effects of Oil Dispersant on Solubilization, Sorption and Desorption of Polycyclic Aromatic Hydrocarbons in Sediment-Seawater Systems." *Marine Pollution Bulletin* 92: 160–169. https://doi.org/10.1016/j.marpolbul.2014.12.042.

Zuur, A. F., and E. N. Leno. 2025. The World of Zero-Inflated Models: Using GLLVM. Highland Statistics Ltd.

Supporting Information

Additional Supporting Information may be found in the online version of this article.

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