Article

Spatial and Temporal Responses of Macrozoobenthic Communities to Environmental Stressors Around Offshore Gas Structures in the Adriatic Sea

Elisa Punzo * , Deborah D’Angelo , Kevin De Simone , Alessandra Spagnolo , Pierluigi Strafella ,
Angela Santelli

Posted Date: 25 March 2026

doi: 10.20944/preprints202603.1986.v1

Keywords: offshore gas structures; macrozoobenthos; soft-bottom; Adriatic Sea; environmental stressor; decommissioning

doi:10.20944/preprints202603.1986.v1

Article

Spatial and Temporal Responses of Macrozoobenthic Communities to Environmental Stressors Around Offshore Gas Structures in the Adriatic Sea

Elisa Punzo [1,2,*], Deborah D'Angelo [1], Kevin De Simone [1], Alessandra Spagnolo [1], Pierluigi Strafella [1,2] and Angela Santelli [1]

[1] IRBIM-CNR Institute for Marine Biological Resources and Biotechnology, Largo Fiera della Pesca 2, 60125, Ancona, Italy
[2] NBFC National Biodiversity Future Center, Piazza Marina 61, 90133, Palermo, Italy
* Correspondence: elisa.punzo@cnr.it

Abstract

Spatial and temporal variability of macrozoobenthic communities were assessed around three newly deployed gas structures in the NW Adriatic Sea (a subsea well-site, a four-leg platform, and a one-leg platform). Four post-installation surveys (two per year over two years) were conducted by sampling sediments at 0, 30, 60, 120 and 1000 m from each structure. All structures showed significant temporal shifts and distance-related differences in community composition. Near-field stations (0-60 m) most frequently accounted for spatial dissimilarities, whereas communities at 120 and 1000 m were generally more similar. Early surveys around the well-site and the four-leg platform were characterised by low diversity and high dominance of the opportunistic polychaete *Ditrupa arietina*, suggesting a short-term disturbance related to installation. Recovery trajectories differed among structures: community descriptors stabilized faster around the subsea well-site, while changes near the platforms extended for at least two years; at the one-leg and four-leg platforms the progressive development of a bivalve mound coincided with a marked differentiation of the benthos at 0 m. Overall, our results highlight that both structural complexity and local environmental settings modulate the spatial footprint and recovery time of benthic communities around offshore installations, supporting a case-by-case approach in decommissioning planning.

Keywords: offshore gas structures; macrozoobenthos; soft-bottom; Adriatic Sea; environmental stressor; decommissioning

1. Introduction

The Adriatic Sea is characterized by eutrophic waters and is subject to multiple, often synergistic, human-induced pressures, including coastal development (high urban density, harbors, and marinas) and protection, tourism, fisheries, aquaculture and river runoff. In addition, the Italian sector hosts one of the highest concentrations of offshore infrastructures in the Mediterranean basin, with more than 120 offshore gas platforms [1,2] and an extensive network of about 300 pipelines extending for a total of around 2300 km [3].

Offshore platforms for oil and gas extraction represent the worldwide largest man-made structures in the marine environment [4,5] and their number has strongly increased in recent decades, driven by the exploitation and research of not-renewable resources.

Beyond their primary function, offshore structures are increasingly recognised for their contribution to ecosystem services [6,7], providing novel hard-substrate habitats in predominantly soft-bottom shelf seas and potentially altering local biodiversity patterns and ecosystem processes. By introducing vertical relief and structural complexity, platforms modify near-bed hydrodynamics, sedimentation rates and trophic pathways, often functioning as artificial reefs ("rig-to-reefs") that

doi:10.20944/preprints202603.1986.v1

host diverse fouling and reef-associated assemblages [8–12]. In some cases, offshore structures have been reported to support high secondary production and biomass, comparable to or exceeding that of natural reefs [13].

Offshore installations may also enhance ecological connectivity by acting as stepping stones for benthic and pelagic organisms across otherwise fragmented habitats [14,15]. However, drilling and installation activities can induce short- to medium-term disturbances in adjacent soft-bottom communities through sediment resuspension, organic enrichment and contaminant release, potentially leading to reduced diversity and altered ecosystem functioning in near-field areas [16–18]. These contrasting roles, as disturbance sources and as habitat-forming structures, highlight the need for site-specific assessments of their ecological footprint.

In the Mediterranean Sea, one of the most anthropogenically impacted marine regions globally [19], the ecological implications of offshore infrastructures must be interpreted within a context of cumulative pressures. Similarly, in the Adriatic Sea, where a high density of gas platforms co-occurs with intense fisheries, marine traffic, coastal development and riverine inputs, understanding how structural characteristics and local environmental conditions modulate benthic responses is particularly relevant.

The ecological effects of platforms on the surrounding environment are often assessed using benthic organisms, which are widely considered reliable environmental quality indicators due to their relatively sedentary nature, long life-spans, ability to integrate stressors over time and the coexistence of species with different sensitivities and tolerances. In addition, benthic communities play an important role in recycling nutrients and materials between the sediments and the overlying water column [20,21]. Following disturbance, the recovery of benthic assemblages is often reported as relatively fast, typically within months to a few years [8,22].

However, the magnitude and duration of platform-related effects are governed by complex interactions among environmental conditions, the characteristics of the structure (dimension, height, material, complexity), and the nature and intensity of the disturbance [23,24].

As numerous offshore installations approach the end of their operational life, decommissioning decisions have become a key management challenge [25,26]. Recent studies e.g., [27,28] highlight that removal options may have contrasting ecological consequences, ranging from habitat loss to potential benefits if structures are partially retained under rigs-to-reefs scenarios. Therefore, robust, site-specific assessments of spatial footprint, temporal recovery, and structural complexity effects are essential to support environmentally sound decommissioning strategies [1,29,30].

The present study provides a comparative assessment of the spatial distribution and temporal variability of macrozoobenthic communities around three offshore gas structures with contrasting architecture, including a subsea production system. Specifically, we tested the null hypothesis that macrozoobenthic abundance, diversity, and community composition do not differ among distances from the structure across four post-installation surveys, implying no effect of the structure on the macrozoobenthic community.

2. Materials and Methods

2.1. Study Area and Sampling Design

The study was conducted in the Italian sector of the north-central Adriatic Sea (Figure 1). Three offshore gas structures with different architecture (Figure 2), a subsea production system, a four-leg platform, and a one-leg platform, were surveyed over a two-year period, starting immediately after deployment (four surveys in total; two surveys per year).

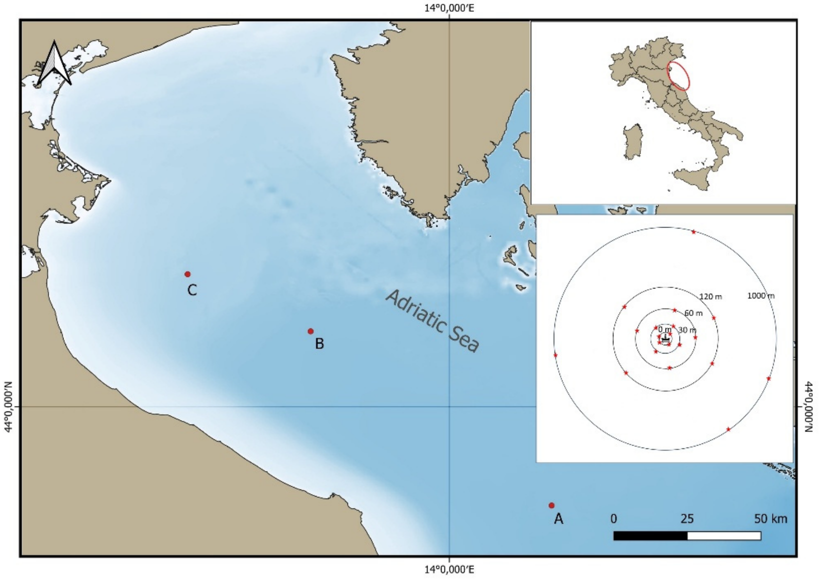

Figure 1. Location of the investigated structures (A, B, and C). A scheme of the sampling strategy is also reported (not in scale) Red stars indicate the sampling sites randomly selected. .

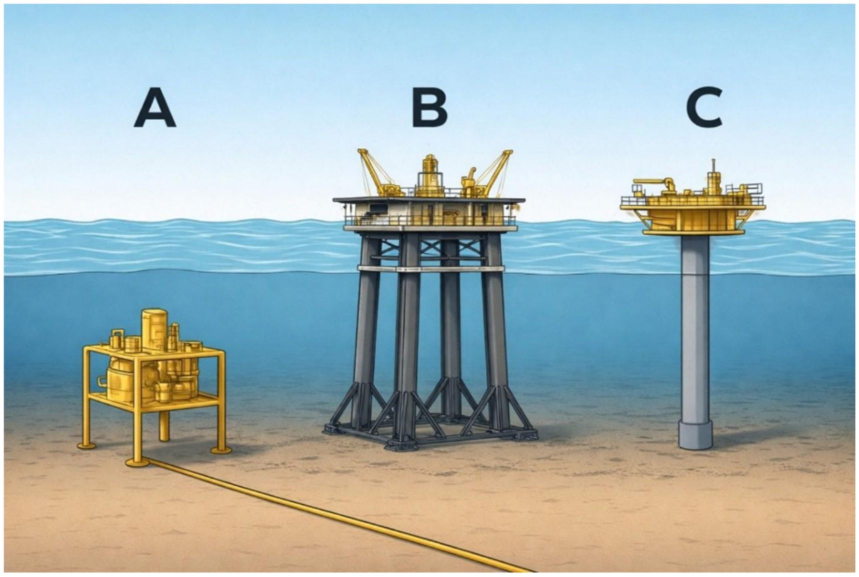

Figure 2. Schematic drawing of the three structures placed on the sediment (A: subsea production system; B: four-leg platform; C: one-leg platform). Not on scale. Image generated using artificial intelligence (Gemini, Google), and reviewed by the authors.

The subsea production system (Structure A) is located 56 km offshore Ancona (central Adriatic Sea) at 80 m depth on a sandy bottom. It consists of two well sites positioned 6.5 m apart (centre-to-centre) within a protective structure extending up to 5 m above the seabed. The area is characterized by variable currents that influence the spatial distribution of the sediments.

The second structure (Structure B) is a four-leg gas platform located 59 km offshore Pesaro (northern Adriatic Sea) at 60 m water depth. The seabed is characterized by offshore relict sands. The site is influenced by the Western Adriatic current, but it can be episodically affected by strong near-bottom hydrodynamics driven by dense shelf-water outflows formed in the northern Adriatic during winter, which can modify sediment redistribution [31]. In addition, the upper water column (10-20

m) can be affected by strong northerly Bora winds, which may alter surface currents and sea-surface temperature.

The third structure (Structure C) is a one-leg gas platform located 46 km offshore Cervia (northern Adriatic Sea) at 42 m water depth on a sand–muddy bottom. This platform is installed farther north than the other two structures in a zone strongly influenced by Po River inputs; it is characterized by variable currents, modulated by both meteorological and hydrodynamic processes, which can affect biogeochemical properties and the spatial distribution of sediments.

The sampling design followed a 'gradient design' approach [32], which is particularly useful when the intensity of a stressor attenuates with distance from the source. This approach has been adopted in previous studies in the Adriatic Sea e.g., [3,8,33–37].

In each survey and for each structure, four sampling stations were randomly selected at increasing distances from each structure: approximately 5 m from the base (hereafter referred to as 0 m), and at 30, 60, 120 and 1000 m. At each station, six samples were collected using a Van Veen grab (capacity 13 L; surface area 0.095 m^2). Samples were sieved on board through a 0.5 mm mesh and all organisms retained were fixed in 5% buffered formalin and preserved in 70% ethanol.

In the laboratory, macrofauna was sorted under a stereomicroscope and a binocular microscope, identified to the species level, when possible, following the World Register of Marine Species [38], counted and weighed.

2.2. Data Analysis

The null hypothesis of the study was that abundance (*N*), species richness (*S*), Shannon Diversity index (*H'*) [39], and Simpson index (λ) [40], as well as macrozoobenthic community composition, do not differ among distances from the structure and sampling surveys.

To test this hypothesis in the univariate context, two-way ANOVAs were performed separately for each structure, with Distance (five levels) and Survey (four levels) as fixed factors. In case of significant interactions among factors, one-way ANOVAs were used to test the effect of Distance within each survey. Prior to performing ANOVAs, normality and homogeneity of variances were evaluated using the Kolmogorov-Smirnov and Bartlett tests, respectively [41]. Spatial and temporal changes in community composition were assessed using permutational multivariate analysis (PERMANOVA) implemented in PRIMER v6 (6.1.11) and PERMANOVA+ add-on [42,43].

Prior to multivariate analysis, species abundance data were square-root transformed to reduce the influence of dominant taxa and increase the contribution of less abundant species. Afterwards, Bray-Curtis similarity matrix was calculated.

For each structure, multivariate patterns of variation among Survey and Distance were tested using two-way PERMANOVA; significant terms were further explored using pair-wise comparisons. Similarity percentage analysis (SIMPER) [44,45] was applied to identify the taxa contributing most to dissimilarity between and similarity within Distance and Survey groups. The significance level was set at $p<0.05$.

3. Results

3.1. Structure A

A total of 233 macrozoobenthic taxa were found at the Structure A, including 88 polychaetes, 57 mollusks, 55 crustaceans, 12 echinoderms, 7 cnidarians, 5 sipunculids, 4 bryozoans, 2 ascidians and 3 other minor taxa. Overall, the macrozoobenthic community consisted mostly of taxa typical of mud and sand habitats.

N and S differed significantly among surveys, whereas no significant differences were detected among distances within each survey (Figure 3; Table A1). Tukey's post-hoc tests indicated that N and S during the fourth survey were significantly higher than in all other sampling periods ($p<0.05$). In addition, S showed significant differences between the first and following surveys ($p<0.05$), with higher values observed in all subsequent ones.

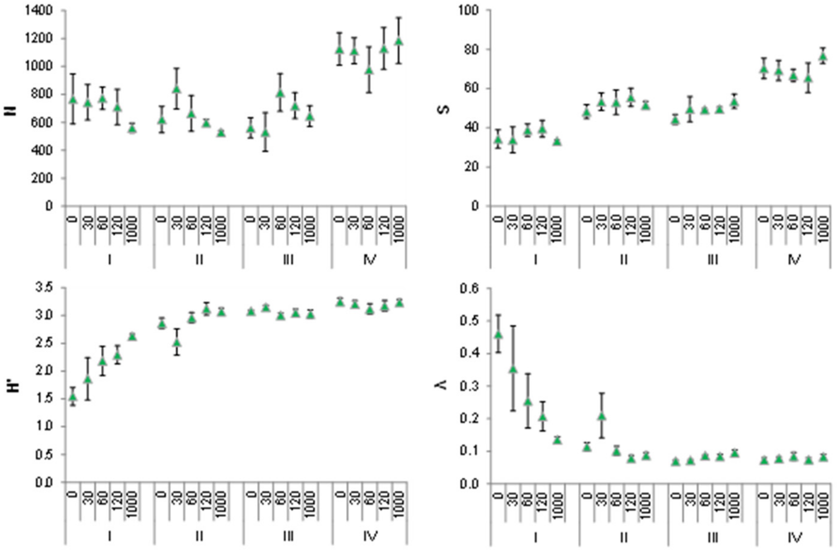

Figure 3. Mean values of univariate indices of macrozoobenthic communities at increasing distance from Structure A across the four surveys. N: abundance (number of individuals m^{-2}); S: species richness; H’: Shannon Diversity index; λ: Simpson index. Error bars refer to standard errors.

H′ and λ indices varied significantly among sampling sites, which was also reflected in a significant interaction Survey × Distance (Table A1). During the first sampling period the lowest H’ value was recorded at 0 m (1.54±0.16) and the highest at 1000 m (2.63±0.04; Figure 3). Pairwise comparisons indicated significant differences for 0 m vs. 120 m and 1000 m, and for 1000 m vs. 30 m and 120 m. The highest λ value occurred at 0 m (0.46±0.06), significantly higher than at 1000 m (0.14±0.01; Figure 3), mainly due to the strong dominance of the polychaete *Ditrupa arietina* (O. F. Müller, 1776) at 0 m.

Both H’ and λ indices varied significantly between the first survey and all the subsequent ones ($p<0.05$). Overall, macrozoobenthic assemblages in the first survey were less diversified and more strongly dominated by a few taxa (e.g., *D. arietina*).

PERMANOVA highlighted significant differences in macrozoobenthic community composition among both Distance and Survey for Structure A (Table 1). Pair-wise tests indicated that communities at 0 m and 30 m differed significantly from those at 120 m and 1000 m, and that zoobenthic assemblages at 60 m differed from those at 1000 m.

Table 1. Results of two-way PERMANOVA and Pair-wise tests analyzing differences among macrozoobenthic assemblages at increasing distance from Structure A during the four surveys. ** = highly significant (P<0.01). .

Source	d.f.	MS	Pseudo-F	P(perm)	Perms
Survey (Su)	3	5261.3	5.7299	0.001**	999
Distance (Di)	4	1209.3	1.3171	0.002**	999
Di x Su	12	991.26	1.0796	0.055	993
Residual	60	918.21			
Total	79				
Pair-wise tests for term Di					
0m ≠ 120m; 1000m	30m ≠ 120m; 1000m		60m ≠ 1000m		

SIMPER analysis revealed the greatest dissimilarity (49%) between communities at 0 m and 1000 m (Table S1). Such dissimilarity was mostly explained by the high abundance of *D. arietina* and the low density of other taxa (e.g. *Paradiopatra calliopae* Arvantidis & Koukouras, 1997, Paraonidae nd and

Nothria conchylega (Sars, 1835)) at 0 m. The largest turnover of species on the temporal scale (58%) occurred between the first and the last survey (Table S1).

3.2. Structure B

A total of 283 taxa were recorded around the Structure B: 88 polychaetes, 80 mollusks, 78 crustaceans, 14 echinoderms, 8 cnidarians, 5 bryozoans, 3 sipunculids, 2 ascidians, and 5 other minor taxa. The community mostly consisted of taxa typical of muddy and sandy habitats; however, from the third survey onwards, some hard-bottom species (mainly the mussel *Mytilus galloprovincialis* Lamarck, 1819 and the serpulid polychaetes) were also recorded close to the platform.

N differed significantly among surveys (Figure 4; Table A2), whereas no significant differences were detected among distances. Tukey's post-hoc test indicated significant differences ($p<0.05$) between the last survey and all previous surveys.

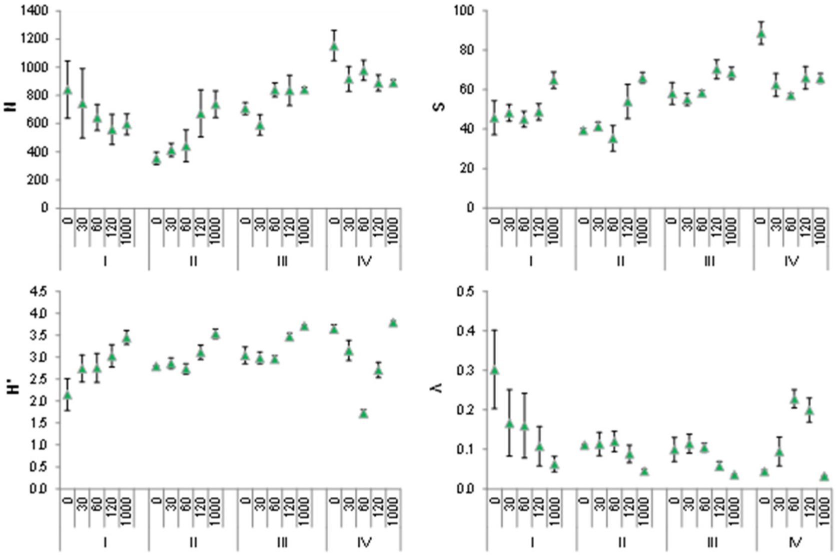

Figure 4. Mean values of univariate indices of macrozoobenthic communities at increasing distance from Structure B during the four surveys. N: abundance (number of individuals m^{-2}); S: species richness; H': Shannon Diversity index; λ: Simpson index. Error bars refer to standard errors.

S showed a pattern similar to that observed for N, with the exception of the first survey (Figure 4). Significant effects were evidenced for both Survey and Distance, but not for their interaction (Table A2). In the first survey, the highest value was recorded at 1000 m (64.8±4.2), even though it did not differ significantly from the other distances. During the second survey, S differed only between 60 m and 1000 m, with the higher values at the latter. No significant differences among distance were detected in the third survey. During the fourth sampling event, the highest value was registered at 0 m (88.7±5.7), resulting statistically different in respect to 30 m (62.3±5.8), 60 m (57.0±1.1) and 1000 m (65.7±2.5).

Both H' and λ showed survey-specific spatial patterns, with a significant Survey × Distance interaction (Figure 4; Table A2). For H', no significant differences among distances were detected in the first two surveys, while in the third sampling period the highest value was recorded at 1000 m, significant different from 0, 30 and 60 m. In the fourth survey, H' was highest at 1000 m (3.79±0.03) and lowest at 60 m (1.72±0.08), with significant differences between these and most other distance pairs.

Within each survey, λ generally mirrored the pattern observed for H'. No significant differences among distances were detected in the first two surveys; in the third survey, 0 m and 30 m differed significantly from 1000 m. In the fourth survey, λ was highest at 60 m and lowest at 1000 m, with significant differences among most distances (Figure 4; Table A2).

doi:10.20944/preprints202603.1986.v1

PERMANOVA indicated significant effects of Distance, Survey and their interaction at Structure B (Table 2), suggesting a potential effect of the four-leg platform on the spatial and temporal variation of macrozoobenthic communities. Pair-wise test revealed a different spatial pattern at each sampling survey (Table 2).

Table 2. Results of two-way PERMANOVA and Pair-wise tests analyzing differences among macrozoobenthic assemblages at increasing distance from Structure B during the four surveys. ** = highly significant (P<0.01). .

Source	d.f.	MS	Pseudo-F	P(perm)	Perms
Survey (Su)	3	2479.7	3.3931	0.001**	999
Distance (Di)	4	2749.6	3.7625	0.001**	997
Di x Su	12	1077.4	1.4743	0.001**	990
Residual	60	717.75			
Total	79				

Pair-wise tests for term Su x Di

I Su	II Su	III Su	IV Su
0m ≠ 60m; 120m; 1000m	0m ≠120m; 1000m	0m ≠ 60m; 120m; 1000m	0m≠120m; 1000m
1000m ≠ 30m; 60m; 120m	30m≠120m; 1000m		
	60m≠120m		

SIMPER analysis showed the highest dissimilarity between 0 m and 1000 m sites (63%; Table S2). The exclusive presence of some taxa and/or the higher abundance of others at 0 m (e.g., the mollusk *Falcidens gutturosus* (Kowalevsky, 1901), the polychaetes *Capitella capitata* (Fabricius, 1780), *Ampharete acutifrons* (Grube, 1860) and *Owenia fusiformis* (Delle Chiaje, 1844)) were the major contributors to this dissimilarity.

On temporal scale, the highest dissimilarity (55%) was found between the first and the last survey, while the lowest one (51%) occurred between the first and the second survey (Table S2).

3.3. Structure C

A total of 260 taxa were recorded at Structure C, including 88 polychaetes, 74 mollusks, 66 crustaceans, 14 echinoderms, 6 cnidarians, 4 sipunculids, 2 ascidians, 2 bryozoans and 4 other minor taxa. The community mostly consisted of taxa typical of muddy and sandy soft bottoms. However, as for Structure B, close to the platform some hard-bottom species were also observed, especially mollusks (e.g., *M. galloprovincialis* and *Neopycnodonte cochlear* (Poli, 1795)), crustaceans (e.g., *Pilumnus hirtellus* (Linnaeus, 1761), *P. spinifer* H. Milne Edwards, 1834 and *Galathea* spp.) and polychaetes (e.g., *Hydroides norvegica* Gunnerus, 1768, *Spirobranchus triqueter* (Linnaeus, 1758)). The occurrence of these taxa increased from the third survey onwards.

N and S displayed survey-specific spatial trends, resulting in a significant Survey × Distance interaction (Figure 5; Table A3). For both indices no significant differences among distances were observed in the two first surveys (p>0.05). In contrast, during the third and fourth sampling periods, higher values were recorded at 0 m compared to the furthest sites (p<0.05), with the exception of 30 m. In particular, in the last two surveys the mean abundance at 0 m was approximately double that those measured at the other distances.

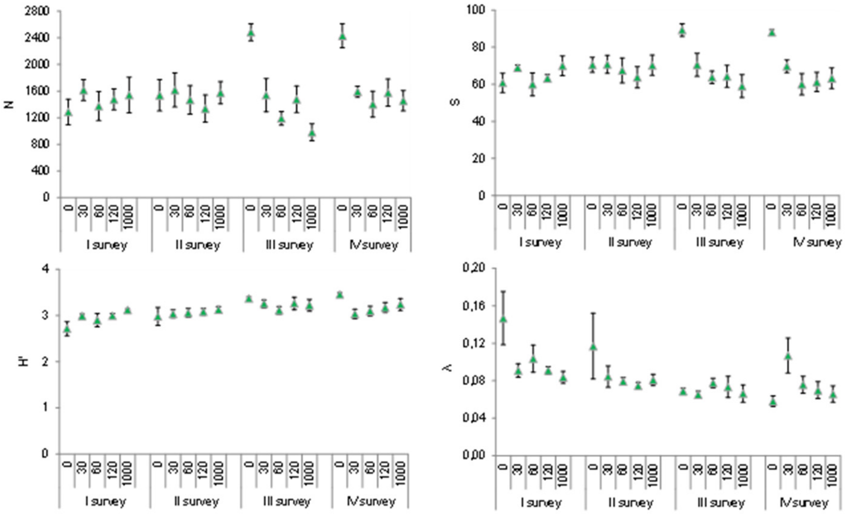

Figure 5. Mean values of univariate indices of macrozoobenthic communities at increasing distance from Structure C during the four surveys. N: abundance (number of individuals m^{-2}); S: species richness; H': Shannon Diversity index; λ: Simpson index. Error bars refer to standard errors.

H' did not show differences within the factor Distance (Figure 5; Table A3), but increased from the third survey onwards, with significant differences between the first and the last two samplings.

Finally, λ displayed a significant effect of Survey and a significant Survey × Distance interaction (Figure 5; Table A3). Considering Survey within each distance, significantly higher λ values were recorded only at 0 m during the first survey compared with the last two ones.

PERMANOVA indicated significant differences within factor Survey, Distance and their interactions (Table 3), suggesting a potential effect of the platform on the spatial and temporal variations of macrozoobenthic communities.

Table 3. Results of 2-way PERMANOVA and Pair-wise tests analyzing differences among macrozoobenthic assemblages at increasing distance from Structure C during the four surveys. * = significant (P<0.05); ** = highly significant (P<0.01). .

Source	d.f.	MS	Pseudo-F	P(perm)	Perms
Survey (Su)	3	2825.5	4.7081	0.001**	996
Distance (Di)	4	2135	3.5575	0.001**	996
Su x Di	12	842.64	1.4041	0.001**	994
Residual	60	600.13			
Total	79				

Pair-wise tests for term Su x Di

I Su	II Su	III Su	IV Su
0m ≠ 1000m	0m ≠ 120m; 1000m	0m ≠ 30m; 60m; 120m; 1000m	0m ≠ 30m; 60m; 120m; 1000m

Pair-wise comparisons revealed that 0 m sites differed from 1000 m in the first survey and became significantly different from all the other distances in the last two sampling periods, whereas no significant differences were detected among the other distances (Table 3).

SIMPER analysis showed the highest dissimilarities between 0 m sites and all other distances (Table S3). The exclusive presence and/or higher abundance of some taxa (e.g., the bivalves Anomia ephippium Linnaeus, 1758 and *Kurtiella bidentata* (Montagu, 1803), and the polychaetes *Sternaspis*

doi:10.20944/preprints202603.1986.v1

scutata (Ranzani, 1817) and *Prionospio cirrifera* Wirén, 1883) at 0 m were major contributors to these dissimilarities (Table S3).

4. Discussion

Since the early 1960s, a high number of offshore gas extraction platforms and related structures have been installed in the Adriatic Sea [1,46]. Many of these installations are approaching the end of their productive life, making decommissioning decisions increasingly relevant [1]. There is now a clear awareness that offshore structures (e.g., extraction platforms, wind farms) themselves become part of the environment where they are placed, providing useful ecosystem function and services [47–50], especially if installed on soft seabed which is known to support lower epibenthic community diversity [51]. Indeed, biogenic deposits (shells, fragments, and dead material) produced by natural dislodgement or structure maintenance increase seabed heterogeneity; coupled with the platforms' water-column-spanning footprint, this results in a unique habitat. Many aquatic organisms colonize these substrates or assemble nearby seeking orientation cues, protection, and greater food availability.

In this context, collecting science-based evidence on the magnitude, spatial footprint and recovery trajectories of platform-related effects on benthic ecosystems is essential to support environmental management [16,52].

This study investigated the spatial and temporal variability of macrozoobenthic communities surrounding three offshore gas structures (one subsea well-site, one four-leg platform and one one-leg platform) in the Adriatic Sea.

Both univariate and multivariate analyses highlighted spatial patterns and temporal changes in macrozoobenthic communities around structures with different architectural complexity. These patterns suggest that differences in community stock and composition among the three installations may be related, at least in part, to structural characteristics (e.g., size and shape). Nevertheless, given the different geographic settings, local environmental conditions are also likely to contribute to the observed variability.

During the first survey carried out just after the structures' installation, a low-diversity assemblage was recorded close to the well-site, as well as near the four-leg platform. In both cases, sediments close to the structures were dominated by the polychaete *Ditrupa arietina*. This species is widely distributed across Mediterranean soft-bottom habitats, ranges from 0 to 150 m and is commonly considered a pioneer taxon that can increase in abundance during the development of transitional communities after environmental changes, such as dredging operations [53]. Pérès and Picard [54] also associated *D. arietina* with unstable soft sediments. Altogether, these observations suggest that the dominance of *D. arietina* during the early phase of the study may be linked to installation-related disturbance, supporting previous evidence that installation activities can substantially affect recipient benthic habitats [8,37,55-57].

From the second survey onward at the well-site, community descriptors (N, S, H′ and λ) became more homogeneous among distances and generally increased (or decreased in the case of λ) towards the last survey.

In contrast, close to the four-leg platform, slightly higher abundance and species richness values were evident only during the fourth survey. These results suggest that recovery of macrozoobenthic communities after installation may occur faster around subsea well-site structures (months) than around larger platform typologies (≥2 years), potentially reflecting differences in the dimensions of the structures and the intensity/modality of installation and drilling activities. Similar recovery times have been reported for other Adriatic platforms at comparable depths [8,37].

At the one-leg platform, the timing and trajectory of change differed from those observed at the other installations. Signs of an early, installation-related impact on macrozoobenthos were not evident, and the community descriptors remained relatively homogeneous among distances during the first two surveys. From the third survey onwards, however, abundance and species richness increased at 0 m.

The recovery pattern observed at both four- and one-leg platforms coincided with the development of a mussel/oyster mound (mainly *Mytilus galloprovincialis* and *Neopycnodonte cochlear*) whose individuals fell from the submerged parts of the structures, confirming the ability of offshore platforms to host extensive fouling communities close to them [8,33,34,58–62]. The development of such mussel mound can facilitate the establishment of diverse assemblages including both soft- and hard-bottom taxa (e.g., decapods *Pilumnus hirtellus*, *Pilumnus spinifer* and *Galathea* spp.; bivalves *Hiatella arctica* (Linnaeus, 1767) and *Anomia ephippium*; and polychaetes *Hydroides* spp. and *Spirobranchus triqueter*). These results align with those reported from other seas around the world e.g., [62–64], indicating that Adriatic platforms may also similarly function as natural biogenic structures (e.g., seagrass meadows, kelp forests and coral habitats) that act as ecosystem engineers, enhancing habitat complexity and facilitating the colonization of associated fauna [65–67]. Corroborating this, the “Barbara” platforms (Adriatic sea) fall within a designated Zone of Biological Protection as defined by the Italian decree [68], acting as a spawning and nursery ground for commercially valuable fish species, whose occurrence may be strictly connected with either prey availability and the occurrence of mussel mounds and thus creating a suitable habitat.

However, apparent increases in macrozoobenthic abundance and biodiversity should be interpreted cautiously: they may reflect localized attraction or concentration processes and/or organic enrichment. In the Adriatic Sea, sedimentary organic matter analyses around offshore gas structures suggest limited spatial gradients in trophic status [69], supporting the need to interpret benthic responses in the context of multiple, interacting mechanisms.

Overall, the present study confirms that geographic setting and ecological context can modulate both the magnitude and the timing of platform-related effects and post-installation resilience, as observed in previous Adriatic case studies e.g., [8,70].

Our results also indicate that structural complexity (as a combination of size and shape) can differentially influence the spatial extent of benthic changes and the time required to reach a more diversified and stable community. Although the present dataset is spatially and temporally limited, it highlights that platform effects are not uniform and can vary substantially among structures and settings.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Summary of SIMPER analysis for Structure A; Table S2: Summary of SIMPER analysis for Structure B; Table S3: Summary of SIMPER analysis for Structure C.

Author Contributions: Conceptualization, E.P.; formal analysis, E.P.; data collection, E.P., P.S. and A.S.; writing—original draft preparation, E.P.; writing—review and editing, E.P., A.S., A.Sp., P.S., D.D., and K.D.; funding acquisition, A.Sp. All authors have read and agreed to the published version of the manuscript.

Funding: The research is carried out with the financial support of ENI S.p.A.—UPSTREAM DICS.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank Gianna Fabi for her valuable support and contribution to this research. Her expertise and assistance were greatly appreciated during the development of this work and for funding acquisition. We appreciate the help of the crew of the RV Tecnopesca II, that was employed in sampling operations and of many members of the “Benthos Laboratory” of CNR-IRBIM during taxonomic analyses.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Results of two-way ANOVA applied to mean values of abundance (N), species richness (S), Shannon Diversity index (H’) and Simpson index (λ) at each site during the four surveys carried out at Structure A. * =

significant (P<0.05); ** = highly significant (P<0.01). d.f. = degree freedom; MS = Mean sum of squares; F = Fisher value.

Source	d.f.	N			S		
		MS	F	P	MS	F	P
Survey	3	0.243	11.026	0.000**	0.275	37.092	0.000**
Distance	4	0.021	0.970	0.430	0.004	0.563	0.691
Survey x Distance	12	0.047	2.136	0.270	0.005	0.705	0.740
Source	**d.f.**	**H’**			**λ**		
		MS	F	P	MS	F	P
Survey	3	0.169	34.568	0.000**	1.041	55.319	0.000**
Distance	4	0.014	2.877	0.030*	0.054	2.895	0.029*
Survey x Distance	12	0.010	2.016	0.038*	0.064	3.394	0.001**

Table A2. Results of two-way ANOVA applied to mean values of abundance (N), species richness (S), Shannon Diversity index (H’) and Simpson index (λ) at each site during the four surveys carried out at Structure B. * = significant (P<0.05); ** = highly significant (P<0.01). d.f. = degree freedom; MS = Mean sum of squares; F = Fisher value.

Source	d.f.	N			S		
		MS	F	P	MS	F	P
Survey	3	0.259	8.612	0.000**	0.106	12.174	0.000**
Distance	4	0.017	0.577	0.681	0.041	4.686	0.003**
Survey x Distance	12	0.026	0.858	0.593	0.014	1.570	0.133
Source	**d.f.**	**H’**			**λ**		
		MS	F	P	MS	F	P
Survey	3	0.015	3.121	0.034*	0.117	2.307	0.088
Distance	4	0.046	9.393	0.000**	0.594	11.693	0.000**
Survey x Distance	12	0.017	3.483	0.001**	0.194	3.812	0.000**

Table A3. Results of two-way ANOVA applied to mean values of abundance (N), species richness (S), Shannon Diversity index (H’) and Simpson index (λ) at each site during the four surveys carried out at Structure C. * = significant (P<0.05); ** = highly significant (P<0.01). d.f. = degree freedom; MS = Mean sum of squares; F = Fisher value.

Source	d.f.	N			S		
		MS	F	P	MS	F	P
Survey	3	0.017	1.256	0.298	0.005	1.182	0.324
Distance	4	0.054	4.125	0.005**	0.019	4.214	0.005**
Survey x Distance	12	0.030	2.299	0.017*	0.009	2.007	0.039*
Source	**d.f.**	**H’**			**λ**		
		MS	F	P	MS	F	P
Survey	3	0.008	8.366	0.000**	0.101	8.982	0.000**
Distance	4	0.001	0.932	0.452	0.017	1.504	0.212
Survey x Distance	12	0.001	1.560	0.129	0.022	1.988	0.041*

References

1. Colaleo, G.; Nardo, F.; Azzellino, A.; Vicinanza, D. Decommissioning of Offshore Platforms in Adriatic Sea: The Total Removal Option from a Life Cycle Assessment Perspective. *Energies* **2022**, *15*, 9325, https://doi.org/10.3390/en15249325

2. UNMIG-MASE. Elenco delle piattaforme marine e strutture assimilabili. Available online: https://unmig.mase.gov.it/wp-content/uploads/dati/piattaforme/piattaforme.pdf (accessed on 11 March 2026)
3. Spagnolo, A.; Punzo, E.; Santelli, A.; Scarcella, G.; Strafella, P.; Grati, F.; Fabi, G. Offshore platforms: Comparison of five benthic indicators for assessing the macrozoobenthic stress levels. *Mar. Pollut. Bull.* **2014**, *82*, 55-65, https://doi.org/10.1016/j.marpolbul.2014.03.023
4. Friedlander, A.M.; Ballesteros, E.; Fay, M.; Sala, E. Marine Communities on Oil Platforms in Gabon, West Africa: High Biodiversity Oases in a Low Biodiversity Environment. *PLoS ONE* **2014**, *9(8)*, e103709, doi:10.1371/journal.pone.0103709
5. Amaechi, C.; Reda, A.; Butler, H.O.; Ja'e, I.A.; An, C. Review on Fixed and Floating Offshore Structures. Part I: Types of Platforms with Some Applications. *J. Mar. Sci. Eng.* **2022**, *10*, 1074, doi.org/10.3390/jmse10081074
6. van Elden, S.; Meeuwig, J.J.; Hobbs, R.J.; Hemmi, J.M. Offshore Oil and Gas Platforms as Novel Ecosystems: A Global Perspective. *Front. Mar. Sci.* **2019**, *6*, 548, https://doi.org/10.3389/fmars.2019.00548
7. Gates, A.R., Jones, D.O.B. 2024. Ecological role of offshore structures. *Nat Sustain*, **2024**, *7*, 383–384, https://doi.org/10.1038/s41893-024-01316-8
8. Manoukian, S.; Spagnolo, A.; Scarcella, G.; Punzo, E.; Angelini, R.; Fabi, G. Effects of two offshore gas platforms on soft-bottom benthic communities (northwestern Adriatic Sea, Italy), *Mar. Environ. Res.* **2010**, *70*, 402-410, doi: 10.1016/j.marenvres.2010.08.004
9. Scarcella, G.; Grati, F.; Fabi, G. Temporal and spatial variation of the fish assemblage around a gas platform in the Northern Adriatic Sea, Italy. *Turk. J. Fish. Aquat. Sci.* **2011**, *11*, 433-444. DOI: 10.4194/1303-2712-v11_3_14
10. Gomiero, A.; Spagnolo, A.; De Biasi, A.; Kozinkova, L.; Polidori, P.; Punzo, E.; Santelli, A.; Strafella, P.; Girasole, M.; Dinarelli, S.; Viarengo, A.; Negri, A.; Nasci, C.; Fabi, G. Development of an integrated chemical, biological and ecological approach for impact assessment of Mediterranean off shore gas platforms. *Chem. Ecol.* **2013**, *29(7)*, 620-634, DOI:10.1080/02757540.2013.817562
11. van der Stap, T.; Coolen, J.W.P.; Lindeboom, H.J. Marine Fouling Assemblages on Offshore Gas Platforms in the Southern North Sea: Effects of Depth and Distance from Shore on Biodiversity. *PLoS ONE*, **2016**, *11(1)*, e0146324, https://doi.org/10.1371/journal.pone.0146324
12. Love, M.S.; Claisse, J.T.; Roeper, A. An analysis of the fish assemblages around 23 oil and gas platforms off California with comparisons with natural habitats. *Bull. Mar. Sci.* **2019**, *95*, 477–514, https://doi.org/10.5343/bms.2018.0061
13. Birt, M.; McLean, D.; Case, M.; Jaworski, S.; Speed, C.W.; Pigas, D.; Driessen, D.; Fullwood L.; Harvey, E.; Vaughan, B.; Macreadie, P.I.; Claisse J.T. Contribution of offshore platforms and surrounding habitats to fish production in the Bass Strait, south-east Australia. *Cont. Shelf Res.* **2024**, *274*, 105209, https://doi.org/10.1016/j.csr.2024.105209
14. Coolen, J.W.P.; Boon, A.R.; Crooijmans, R.; van Pelt, H.; Kleissen, F.; Gerla, D.; Beermann, J.; Birchenough, S.N.R.; Becking, L.E.; Luttikhuizen, P.C. Marine stepping-stones: Connectivity of Mytilus edulis populations between offshore energy installations. *Mol Ecol.* **2020**, *29(4)*, 686-703, doi: 10.1111/mec.15364
15. Fowler, A.M.; Jørgensen, A.M.; Coolen, J.W.P.; Jones, D.O.B.; Svendsen, J.C.; Brabant, R.; Rumes, B.; Degraer, S. The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. *ICES J. Mar. Sci*, **2020**, *77*, 1109-1126, doi:10.1093/icesjms/fsz143
16. Cordes, E.E.; Jones, D.O.B.; Schlacher, T.A.; Amon, D.J., Bernardino, A.F., Brooke, S.; Carney, R.; DeLeo, D.M.; Dunlop, K.M.; Escobar-Briones, E.G.; et al. Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. *Front. Environ. Sci.* **2016**, *4*, 58, doi: 10.3389/fenvs.2016.00058
17. Chen Z.; Cameron, T.C.; Couce, E.; Garcia, C.; Hicks, N.; Thomas, G.E.; Thompson, M.S.A.; Whitby, C.; O'Gorman, E.J. Oil and gas platforms degrade benthic invertebrate diversity and alter ecosystem functioning. Sci. Total Environ. **2024**, *929*, 172536. https://doi.org/10.1016/j.scitotenv.2024.172536

18. Beyer, J., Ellingsen, K.E., Yoccoz, N.G., Buhl-Mortensen, P., Bakke, T. Environmental effects monitoring of offshore oil and gas activities on the Norwegian continental shelf: A review. *Mar. Environ. Res.* **2025**, *209*, 107166, https://doi.org/10.1016/j.marenvres.2025.107166
19. Piroddi C.; Colloca, F.; Tsikliras, A.C. The living marine resources in the Mediterranean Sea Large Marine Ecosystem. *Environ Dev*. **2020**, *36*, 100555, doi: 10.1016/j.envdev.2020.100555
20. Rodil, I.F.; Lucena-Moya, P.; Tamelander, T.; Norko, J.; Norkko, A. Seasonal Variability in Benthic-Pelagic Coupling: Quantifying Organic Matter Inputs to the Seafloor and Benthic Macrofauna Using a Multi-Marker Approach. *Front. Mar. Sci*. **2020**, *7*, 404, https://doi: 10.3389/fmars.2020.00404
21. Gammal, J.; Järnström, M.; Norkko, J.; Bonsdorff, E.; Norkko, A. Seasonal Variation in the Role of Benthic Macrofauna Communities for Ecosystem Functioning in Shallow Coastal Soft-Sediment Habitats. *Estuaries Coast* **2025**, *48*, 62, doi.org/10.1007/s12237-025-01499-z
22. Oak, T.G. Oil and gas exploration and production activities in areas with defined benthic conservation objectives: A review of potential impacts and mitigation measures. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/040. vi + 55 p. available online: https://publications.gc.ca/collections/collection_2020/mpo-dfo/fs70-5/Fs70-5-2020-040-eng.pdf
23. Trabucco, B.; Maggi, C.; Manfra, L.; Nonnis, O.; Di Mento, R.; Mannozzi, M.; Virno Lamberti, C.; Cicero, A.M.; Gabellini, M. Monitoring of Impacts of Offshore Platforms in the Adriatic Sea (Italy). In *Advances in Natural Gas Technology*, Al-Megren H. Ed.; InTech, 2012, pp 285-300. https://doi.org/10.5772/38249
24. Lynam, C. P.; Garcia, C.; Chen, Z.; Thomas, G.E.; Hicks, N.; Bolam, S.G.; Russell, D.J.F. Ecological recovery of benthic fauna from contamination near oil and gas platforms. *Mar. Pollut. Bull.* **2025**, *221*, 118470. https://doi.org/10.1016/j.marpolbul.2025.118470
25. Lemasson, A.J.; Someerfield, P.J.; Schratzberger, M.; McNeill, C.L.; Nunes, J.; Pascoe, C.; Watson, S.C.L.; Thompson, M.S.A.; Couce, E.; Knights A.M. Evidence for the effects of decommissioning man-made structures on marine ecosystems globally: a systematic map. Environ Evid **2022**, *11*, 35, https://doi.org/10.1186/s13750-022-00285-9
26. Saeed, A.; Parnun, B. Repurposing oil and gas infrastructure as artificial reefs—a global perspective. Australian Energy Producers Journal **2024** *64(2)*, S516-S519, https://doi.org/10.1071/EP23114
27. Fortune, I.S.; Paterson, D.M. Ecological best practice in decommissioning: a review of scientific research. *ICES J. Mar. Sci.* **2020**, *77(3)*, 1079-109, https://doi.org/10.1093/icesjms/fsy130
28. Knights, A.M., Lemasson, A.J., Firth, L.B., Beaumont, N., Birchenough, F., Claisse, J., Coolen, J.W.P., Copping, A., De Dominicis, M., Degraer, S. et al. To what extent can decommissioning options for marine artificial structures move us toward environmental targets? *J. Environ. Manage.* **2024**, *350*, 119644, https://doi.org/10.1016/j.jenvman.2023.119644
29. Macreadie, P.I.; Fowler, A.M.; Booth, D.J. Rigs-to-reefs: Will the deep sea benefit from artificial habitat? *Front Ecol Environ* **2011**, *9(8)*, 455-461, https://doi.org/10.1890/100112
30. Fowler, A.M.; Macreadie, P.I.; Jones, D.O.B.; Booth, D.J. A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. *Ocean Coast. Manag.* **2014**, *87*, 20-29, https://doi.org/10.1016/j.ocecoaman.2013.10.019
31. Foglini, F.; Campiani, E.; Trincardi F. The reshaping of the South West Adriatic Margin by cascading of dense shelf waters. *Mar. Geol*. **2016**, *375*, 64–81, doi:10.1016/j.margeo.2015.08.011
32. Ellis, J.I.; Schneider, D.C. Evaluation of a gradient sampling design for environmental impact assessment. *Environ. Monit. Assess.* **1997**, *48*, 157-172.
33. Spagnolo, A.; Ausili, S.; Fabi, G.; Manoukian, S.; Puletti, M. Realizzazione di una piattaforma estrattiva offshore: effetti sul macrozoobenthos di fondo mobile. *Biol. Mar. Mediterr.* **2006**, *13*, 60-61.
34. Spagnolo, A.; Manoukian, S.; Punzo, E.; Fabi, G.; Puletti, M.; Tavolini E. Impact of two off-shore gas platforms on the surrounding benthic communities (Western Adriatic Sea, Italy). In Proceedings of the 9th Offshore Mediterranean Conference (OMC), Ravenna, Italy, 25-27 March 2009, 13 pp.
35. Fabi, G.; Manoukian, S.; Spagnolo, A. Impact of an open-sea suspended mussel culture on macrobenthic community (Western Adriatic Sea). *Aquaculture* **2009**, *289*, 54-63, https://doi.org/10.1016/j.aquaculture.2008.12.026

36. Punzo, E.; Strafella, P.; Scarcella, G.; Spagnolo, A.; De Biasi, A.M.; Fabi, G. Trophic structure of polychaetes around an offshore gas platform. *Mar. Pollut. Bull.* **2015**, *99*, 119-125, doi:10.1016/j.marpolbul.2015.07.049
37. Punzo, E.; Gomiero, A.; Tassetti, A.N.; Strafella P.; Santelli, A.; Salvalaggio, V.; Spagnolo, A.; Scarcella, G.; De Biasi, A.M.; Kozinkova, L.; Fabi, G. Environmental impact of offshore gas activities on the benthic environment: a case study. *Environ. Manag.* **2017**, *60*, 340-356, doi:10.1007/s00267-017-0886-4
38. Ahyong, S., Boyko, C.B., Bernot, J., Brandão, S.N., Daly, M., De Grave, S., de Voogd, N.J., Gofas, S., Hernandez, F.; Mees, J.; et al. World Register of Marine Species. 2026. Available online: https://www.marinespecies.org at VLIZ (accessed on 2026-03-06).
39. Shannon, C.E. A Mathematical Theory of Communication. *Bell Syst. Tech. J.* **1948**, *27*, 379–423, 623–656, https://doi.org/10.1002/j.1538-7305.1948.tb01338.x
40. Simpson, H.E. Measurement of diversity. *Nature*, **1949**, *163*, 688
41. Lindman, H.R. Analysis of variance in experimental design. Springer texts in statistics. Springer-Verlag Publishing, New York, USA, 1992, pp 531.
42. Clarke, K.R.; Gorley, R.N. *PRIMER v6: User manual/Tutorial*. 2006. PRIMER-E: Plymouth.
43. Anderson, M.J.; Gorley, R.N.; Clarke, K.R. *PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods*, PRIMER-E, Plymouth, UK, 2008
44. Clarke, K.R. Non-parametric multivariate analyses of changes in community structure. *Aust. J. Ecol.* **1993**, *18*, 117-143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x
45. Clarke, K.R.; Warwick, R.M. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. 2001. Plymouth Marine Laboratory, UK.
46. Spagnolo A.; Cuicchi, C.; De Biasi, A.M.; Ferra C.; Montagnini L.; Punzo, E.; Salvalaggio, V.; Santelli, A.; Strafella, P.; Fabi G. Effects of the installation of offshore pipelines on macrozoobenthic communities (northern and central Adriatic Sea). *Mar. Pollut. Bull.* **2019**, *138*, 534-544, https://doi.org/10.1016/j.marpolbul.2018.12.003
47. Fabi, G.; Grati, F.; Lucchetti, A. Evolution of the fish assemblage around a gas platform in the northern Adriatic sea. *ICES J. Mar. Sci.* **2002**, *59 (1)*, 309-315, https://doi.org/10.1006/jmsc.2002.1194
48. Fabi, G.; Grati, F.; Puletti, M.; Scarcella, G. Effects on fish community induced by installation of two gas platforms in the Adriatic Sea. *Mar. Ecol. Prog. Ser.* **2004**, *273*, 187-194.
49. Claisse, J.T.; Pondella, D.J.; Love, M.; Zahn, L.A.; Williams, C.M.; Williams, J.P.; Bull, A.S. Oil platforms off California are among the most productive marine fish habitats globally. *Proc. Natl. Acad. Sci. USA* **2014**, *111(43)*, 15462-15467, https://doi.org/10.1073/pnas.1411477111
50. Consoli, P.; Mangano, M.C.; Sarà, G.; Romeo, T.; Andaloro F. The influence of habitat complexity on fish assemblages associated with extractive platforms in the central Mediterranean Sea. *Adv. Oceanogr. Limnol.* **2018**, *9(2)*, 59-67, https://doi.org/10.4081/aiol.2018.7918
51. Kingma, E.M.; ter Hofstede, R.; Kardinaal, E.; Bakker, R.; Bittner, O.; van der Weide, B.; Coolen, J.W.P. Guardians of the seabed: Nature-inclusive design of scour protection in offshore wind farms enhances benthic diversity. *J. Sea Res.* **2024**, *199*, 102502, https://doi.org/10.1016/j.seares.2024.102502
52. Sommer, B.; Fowler, A.M.; Macreadie, P.I., Palandro D.A., Aziz, A.C., Booth, D.J. Decommissioning of offshore oil and gas structures—Environmental opportunities and challenges. *Sci. Total Environ*. **2019**, *658*, 973-981 https://doi.org/10.1016/j.scitotenv.2018.12.193
53. Sardà, R.; Pinedo, S.; Grémare, A.; Taboada, S. Changes in the dynamics of shallow sandy-bottom assemblages due to sand extraction in the Catalan Western Mediterranean Sea. *ICES J. Mar. Sci.* **2000**, *57*, 1446-1453, doi:10.1006/jmsc.2000.0922
54. Pérès, J.M.; Picard, J. Nouveau Manuel de Bionomie benthique de la Mer Mediterranée. *Rec. Trav. Stat. Mar. Endoume*, **1964**, *31(47)*, 3-137.
55. Manfra, L.; Maggi, C. An Approach Integrating Chemistry and Toxicity for Monitoring the Offshore Platform Impacts. In *Advances in Natural Gas Technology*, Al-Megren H. Ed.; InTech, 2012, pp 271-284. https://doi.org/10.5772/38246
56. Elbisy, M.S. Environmental Management of Offshore Gas Platforms in Abu Qir Bay, Egypt. *KSCE J. Civ. Eng.* **2015**, 1-14.

doi:10.20944/preprints202603.1986.v1

57. Fortune, I.S.; Madgett, A.S.; Scarborough Bull, A.; Hicks, N.; Love, M.S.; Paterson, D.M. Haven or hell? A perspective on the ecology of offshore oil and gas platforms. *PLOS Sustain. Transform*. **2024**, *3(4)*, e0000104, https://doi.org/10.1371/journal.pstr.0000104
58. Fabi G., Da Ros L., De Biasi A.M., Manoukian S., Nasci C., Puletti M., Punzo E., Spagnolo A. Environmental impact of gas platforms in the Northern Adriatic Sea: a case study. *Rapp. Comm. int. Mer Médit.* **2007**, *38*, 471.
59. Trabucco, B.; Bacci, T.; Marusso, V.; Lomiri, S.; Vani, D.; Marzialetti, S.; Cicero, A.M.; Di Mento, R.M; De Biasi, A.M.; Gabellini, M.; Virno Lamberti, C. Study of the macrofauna surrounding off-shore platforms in the Central Adriatic Sea. *Biol. Mar. Mediterr.* **2008**, *15(1)*, 141-143.
60. Gomiero, A.; De Biasi, A.M.; Da Ros, L.; Nasci, C.; Spagnolo, A.; Fabi, G. A multidisciplinary approach to evaluate the environmental impact of off-shore gas platforms in the western Adriatic Sea. *Chem. Ecol.* **2011**, *27(S2)*, 1-13, http://dx.doi.org/10.1080/02757540.2011.625943
61. Bergmark, P.; Jorgensen, D. *Lophelia pertusa* conservation in the North Sea using obsolete offshore structures as artificial reefs. *Mar. Ecol. Prog. Ser.* **2014**, *516*, 275-280, doi: 10.3354/meps10997
62. Todd, V.L.G., Susini, I., Williamson, L.D., Todd, I.B., McLean, D.L., Macreadie, P.I. Characterizing the second wave of fish and invertebrate colonization of an offshore petroleum platform. *ICES J. Mar. Sci.* **2021**, *78(3)*, 1131–1145, https://doi:10.1093/icesjms/fsaa245
63. Bomkamp, R.E.; Page, H.M.; Dugan, J.E. Role of food subsidies and habitat structure in influencing benthic communities of shell mounds at sites of existing and former offshore oil platforms. *Mar. Biol.* **2004**, *146*, 201-211, https://doi.org/10.1007/s00227-004-1413-8
64. Neira, F.J. Summer and winter plankton fish assemblages around offshore oil and gas platforms in south-eastern Australia. *Estuar. Coast. Shelf Sci.* **2005**, *63*, 589-604, https://doi.org/10.1016/j.ecss.2005.01.003
65. Borthagaray, A.I.; Carranza A. Mussels as ecosystem engineers: Their contribution to species richness in a rocky littoral community. *Acta Oecol.* **2007**, *31*, 243-250, doi:10.1016/j.actao.2006.10.008
66. Cerrano, C.; Danovaro, R.; Gambi, C.; Pusceddu, A.; Riva, A.; Schiaparelli, S. Gold coral (*Savalia savaglia*) and gorgonian forests enhance benthic biodiversity and ecosystem functioning in the mesophotic zone. *Biodivers. Conserv.* **2010**, *19*, 153-167, doi:10.1007/s10531-009-9712-5
67. Arribas, L.P.; Donnarumma, L.; Palomo, M.G.; Scrosati, R.A. Intertidal mussels as ecosystem engineers: their associated invertebrate biodiversity under contrasting wave exposures. *Mar. Biodivers.* **2014**, *44*, 203–211, doi.10.1007/s12526-014-0201-z
68. Ministero delle Politiche Agricole e Forestali. Decreto 16 marzo 2004. Istituzione di una Zona di Tutela Biologica denominata "Area Barbare", Gazzetta Ufficiale della Repubblica Italiana, N. 77, 1 aprile 2004, Italy. Available online: https://www.gazzettaufficiale.it (accessed on 11 March 2026).
69. Punzo, E.; Bianchelli, S.; Pusceddu, A; Salvalaggio, V.; Santelli, A.; Strafella, P.; Fabi, G. Quantity and biochemical composition of sedimentary organic matter around offshore gas extraction platforms of the Adriatic Sea. *Chem. Ecol.* **2017**, *33(1)*, 61-75, https://doi.org/10.1080/02757540.2016.1246543
70. Terlizzi, A.; Bevilacqua, S.; Scuderi, D.; Fiorentino, D.; Guarnieri, G.; Giangrande, A.; Licciano, M.; Felline, S.; Fraschetti, S. Effects of offshore platforms on softbottom macro-benthic assemblages: A case study in a Mediterranean gas field. *Mar. Pollut. Bull.* **2008**, *56*, 1303-1309, DOI: 10.1016/j.marpolbul.2008.04.024