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The re-use of offshore platforms as ecological observatories

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ABSTRACT

The high number of offshore platforms at the end of their productive phase offers the opportunity of their re-use and the development of effective management solutions, such as the possibility of utilizing them as ecological observatories for monitoring marine ecosystems and their biological resources. Here, through a multiparametric observatory deployed at an unproductive offshore platform, located in the Central Adriatic Sea (Mediterranean Sea), we collected data for 13 months on benthopelagic fish assemblage and habitat conditions. A total of 155.5 h of high-frequency (30 min) video-monitoring, recorded higher fish abundances during spring-summer periods during daytime, while fish diversity was highest in autumn. Some environmental variables contributed significantly to explain the overall community variance. Our results suggest that offshore platforms can be re-converted into ecological observatories, to collect relevant amounts of information that can be difficulty obtained with alternative approaches, contributing to our understanding of changes occurring in open water ecosystems.

1. Introduction

Several offshore oil and gas platforms globally distributed are over 30 years old, thus reaching the end of their productive phase or already exhausted (Watson et al., 2023). This is the case of installations located in the Adriatic Sea, which is one of the world's region with the highest concentration of infrastructures for hydrocarbon extraction, with >120 platforms (Maggi et al., 2007).

Thus, there is an urgent need to understand how to proceed with the decommissioning/re-use/conversion of these structures at the end-of-their productive life, also in the context of energy transition and sustainable use of marine space and resources (Birchenough and Degraer, 2020; Martins et al., 2020).

Currently, selecting a proper management strategy for offshore platform decommissioning is a challenge from either an economic, social, and environmental point of view (Bull and Love, 2019). International conventions and guidelines require that offshore structures at the end of their “life” must be removed (Smyth et al., 2015; Watson et al., 2023). However, the important economic costs as well as the potentially significant environmental and ecological impacts of their removal led to a gradual change in international guidelines and paved the way for a more flexible *case-by-case* approach that takes into consideration also a possible reconversion (e.g., installation of alternative and sustainable energy-producing systems, aquaculture farms, etc.), including their relevance as artificial reefs (Fowler et al., 2018; van Elden et al., 2019). Notwithstanding the decommissioning practices vary across countries and regions depending on the legal framework, the potential impact of the decommissioning remains the same and increases depending on the system complexity (Birchenough and Degraer, 2020). The basic and effective monitoring asset proposed in this manuscript may be the same for all platforms and can be upscaled (i.e., multiplied) according to the complexity of the platform system to obtain data at wider spatial scale (Fujii and Jamieson, 2016).

Readaptation of already existing offshore platforms can offer several advantages in the light of the blue economy sustainable strategy (Capobianco et al., 2021), and thus there is growing interest in understanding the ecological and socio-economic benefits of leaving structures in place, at least partially.

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There is evidence that the jacket (i.e., the submerged part) of offshore platforms not only act as a Fish Aggregating Device (FAD) mainly for reef-dwelling or partially reef-dwelling species (Bernstein, 2015), providing shelter from predation and trawling, and abundant food supplies, supporting high local biomass, and finally enhancing local overall diversity (Claisse et al., 2014). Although the characteristics of artificial structures of providing new habitats can distort data from typical environmental observations (Degraer et al., 2020), platforms are a valuable tool for studying seasonal and temporal species dynamics, tracking the presence of alien species, and conducting species composition surveys in the area (Fujii and Jamieson, 2016).

In the Adriatic Sea, limited studies have been carried out to investigate the fish assemblage around oil and gas platforms (e.g., Consoli et al., 2013; Fabi et al., 2002, 2004), and any of these considered high-resolution (at the scale of hours) temporal dataset. Moreover, these studies have predominantly been carried out by using fishing gears (Scarcella et al., 2011a, 2011b), Remotely Operated Vehicles (ROVs) and human-assisted Underwater Visual Census (UVC) techniques (Andaloro et al., 2011).

Nowadays, cabled video-observatories are emerging tools that offer new opportunities for a remote monitoring of the marine environment with minimum footprint (Aguzzi et al., 2012, 2015, 2019; Rountree et al., 2020; Lantieri et al., 2022). Observatory cameras can perform a remote and continuous image collection at high frequencies (from seconds to minutes), over long-time periods (from days and weeks to seasons and years) along with oceanographic and meteorological data (e.g., Aguzzi et al., 2020a, 2020b; Francescangeli et al., 2022). Even though observatories have a limitation in the representation power of ecological data (i.e., cameras portray a limited spatial coverage) they offer a long-term and a low invasive multiparametric technology for the monitoring of marine ecosystems, hardly achievable with other instruments (Rountree et al., 2020). *In situ* video monitoring can provide a record of temporal changes in the number of fish and assemblages structures, providing insights on species swimming rhythms, how their interplay provokes the community turnover at a diel (i.e., 24 h based), and seasonal frequencies, along with a better view of fish ecological niches (via cause-effects studies linking fish count fluctuations with time series of the main physical and chemical variables) (Aguzzi et al., 2013, 2020a, 2020b; Marini et al., 2018). It is worth stressing that the existence of offshore platforms undeniably impacts the environment at local scale, and their re-use of observatories lead to a study of “unnatural environmental conditions” in the area (Degraer et al., 2020). However, platforms can offer insights into long-term ecological processes beyond potential decommissioning impacts, such as species composition or water quality, especially once their productive phase ends. Therefore, these observatories can be used for installing instrument for the long-term monitoring of different biological and oceanographical parameters (Fujii and Jamieson, 2016).

The conversion of offshore platforms into permanent observatories for monitoring marine ecosystems can be more cost-effective than deploying temporary monitoring structures or building new ones, apart from avoiding the potential impacts of the decommissioning of large and ancient or abandoned infrastructures. Additionally, since these platforms have been in the ocean for several decades, they have supported the establishment of complex ecosystems around them (Sommer et al., 2019; Saeed and Parnum, 2024). Given the wide spatial distribution of those platforms in the North and Central Adriatic Sea, their reconversion and coordinated re-use could fulfil the needs for a better assessment of ecosystems health status, as required by the EU Marine Strategy Framework Directive (MSFD 2008/56/EC) for the computing of Descriptors and their related indicators.

In the present study, we show the results of a 1-year survey of the fish assemblage associated to an unproductive offshore platform located in the Central Adriatic Sea (Mediterranean Sea). To do so, a multiparametric cabled-observatory was installed for the continuous and high frequency (1 h time-lapsed) acquisition of videos for fish classification and counting as well as synchronous oceanographic and meteorological data collection. The analysis of multiparametric data was enforced to investigate the occurrence of environmental-driven fluctuations in the local fish assemblage as a proxy for good monitoring practices. The aims of the present study were: *i*) to assess the fish assemblage (in terms of richness) associated to the platform infrastructure and its relevance as abundance and biodiversity hot spot, as well as to analyse day/night and seasonal changes in the defined fish assemblage; *ii*) to characterize the rhythmic swimming behaviour of the most occurring species (as derived by fluctuations in video-counted individuals) for a better understanding of the temporal expression of their niches; and *iii*) to identify the main environmental drivers responsible of such changes for a better comprehension of the potential responses of fish communities in the light of climate change projected scenarios.

2. Materials and methods

2.1. The study site

The offshore platform utilised for the present study is a mono-tubular structure that in 1998 was located in the Central Adriatic Sea at ca. 10 km off the Abruzzo coast and at ca. 20 m water depth (Fig. 1). The platform is classified as “productive not supplying” (https://unmig.mase.gov.it/ricerca-e-coltivazione-di-idrocarburi/pozzi-produttivi/). The observatory associated to the platform, called “Subsea Monitoring Skid (SMS)”, was deployed at the end of January 2021 on the sea bottom, at ca. 20 m of distance and northward with respect to the platform (Lat. 42.65696°N; Long. 14.15498°E), and consists of marine stainless-steel structure (AISI 316) that supports and feed of continuous power an underwater camera and associated devices and multiple sensors (see next section and the technical description of the whole structure and alimentation in the Supplementary material). The platform was anchored at the seabed nearby the tubular structure by a concrete block (total weight of about 1200 kg) (Suppl. Fig. 1).

2.2. Deployed sensors and data acquisition

An IP full-HD underwater camera with 2944 × 1656-pixel resolution H.264/MJPEG compression, with a 1/2.9″ CMOS sensor, streaming and remote recording function, was used to acquire time-lapse footages of 60 s of duration per hour, continuously during day and night. An underwater white LED light was used at nocturnal filming, turning on at the same time as the camera starts recording the videos (OceanCAM-IP/Z, OceanLED-Subsea LED lighting), and remotely controllable through a dedicated server at Stazione Zoologica Anton Dohrn of Naples (Italy) by the LISC (Logical Intelligent System Control) Datalogger and accessible 24-h. This allowed to switch on/off the camera in every moment of the day in addition to the hourly recordings of 60 s described above. The same system was used to control and stream the data from the weather station (see below).

The camera was installed in an underwater housing, pointing always to the same Field of View (FOV- fixed at 103°). The housing also included an integrated device for mechanical cleaning of the optical window (Zebra-Tech Hydro-Wiper). Time-lapse imaging was continuously acquired from the 1st of February 2021 to the 28th of February 2022, for a total of 13 months along with oceanographic data (see below).

The deployed oceanographic sensors were a CTD (MicroCAT SBE37-SI) for measure temperature and salinity (and therefore as proxy of water density), an SBE63 Optical Dissolved Oxygen Sensor (for oxygen measurements), a WetLabs ECO Triplet multi-channel fluorimeter (for measuring turbidity and chlorophyll-*a*), and an Acoustic Doppler Current Profiler (ADCPs, TRDI Monitor 600 kHz) to measure current speed and direction (including height, period, and direction of the waves).

In addition, a weather station was installed on the platform deck and connected to the LISC Datalogger for determining, irradiance, and wind

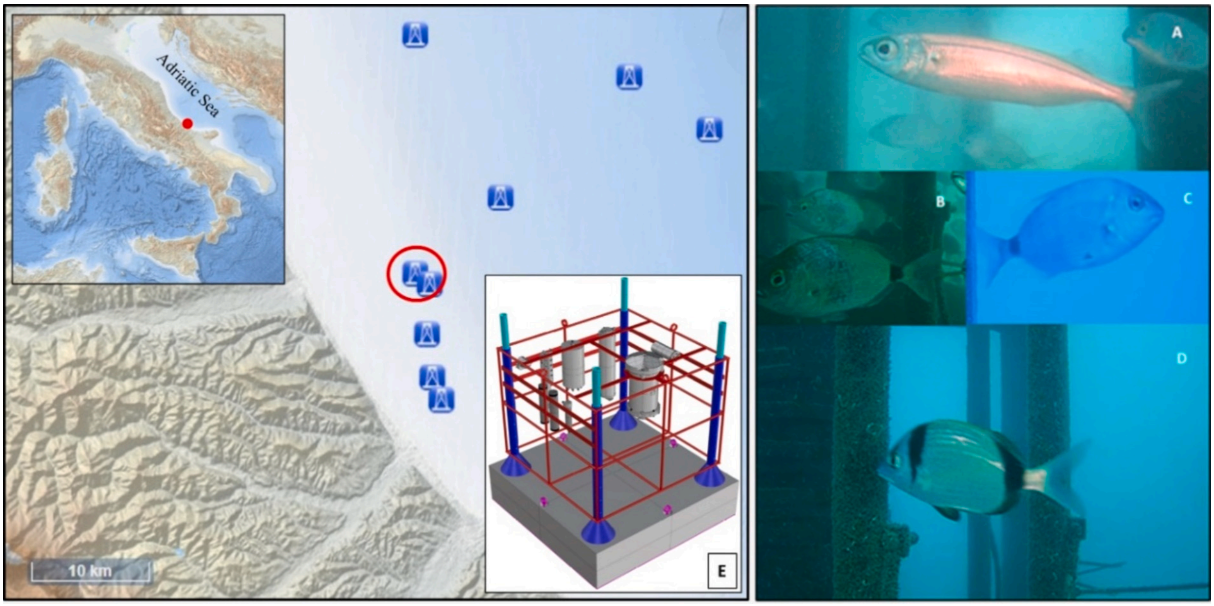

Fig. 1. On the left, map of the Mediterranean Sea and the location of the Subsea Monitoring Skid (SMS) (inset: Lon: 14.15423203E, Lat: 42.65742097N, offshore from the Abruzzo coast), from EMODnet (European Marine Observation and Data Network) Bathymetry and Human activities portals (http://www.emodnet-bathymetry.eu), and the scheme of the structure(E); on the right, snapshots of the most abundant species observed at the SMS located in the Central Adriatic Sea, on the right panel an example of the fish species identified: A) *Boops boops*; B) *Diplodus sargus*; C) *Diplodus annularis*; D) *Diplodus vulgaris*.

direction, speed, and origin (correlated with the direction of wind origin with respect to the North).

To estimate fish diversity, each video was analysed for the presence of all visible individuals, which were classified to the lowest taxonomic level possible, according to international faunal guides (e.g., Louisy, 2020). As a result, time series of fish counts were recorded for all species identified and the category "unidentified". Fish count variations were considered as a proxy of the average swimming activity of each species, being the chance of an animal to be spotted in the camera FOV proportional to its motility rate and overall presence in the area (Francescangeli et al., 2022). Since the probability of spotting animals using video monitoring depends upon rhythmic behaviours such as spatiotemporal displacement through different environments, or alternation of sleeping/activation activities (e.g., Myers et al., 2016), together with fish density itself, the obtained results were considered as a proxy for determining diel (24-h based) and seasonal patterns of changes in local abundance of fish populations.

2.3. *Data processing*

All individuals appearing in videos were classified down to the taxonomic level as possible (see Supplementary video), individuals appearing too distant in the FOV, or impossible to recognize, were classified as "Unidentified". All environmental data were acquired in real time, taking the environmental value at the start of the video. Therefore, time series of data were crunched at the limiting frequency of video acquisition (i.e., one video by hour).

2.4. *Diel and seasonal changes in abundance, diversity, and assemblage composition*

First, an accumulation curve with bootstrapping per each season (blocks of 3 months of observations) was computed as a proxy for the monitoring effort, to measure the performance of eco-monitoring practices by cameras, i.e., how many pictures were necessary to get saturation in species detection.

2.4.1. *Diel and seasonal changes in fish abundance*

To assess day-night changes across seasons, abundance data (i.e., fish counts per hour) were averaged into two temporal blocks (i.e., day and night) accordingly to the irradiance data (values >0 W/m^2 were classified as day, and null values as night), to reduce variance in species count (Aguzzi et al., 2020a, 2020b). Abundance data were first visualized with boxplots for the whole community (square-root transformed data), and day and night samples (untransformed data). Then, changes in total fish abundances between day and night, and among months, were analysed through a two-way Permutational Multivariate Analysis of Variance (PERMANOVA, Anderson et al., 2008) based on the Euclidean resemblance matrix of square root-transformed abundance data followed by pairwise comparisons. The experimental design used for statistical analyses was based on two crossed-fixed factors: 'month', with 13 levels (from February 2021 to February 2022) and 'day/night', with two levels (day and night).

2.4.2. *Day-night variations of fish assemblages' composition across seasons*

Changes in the fish assemblage composition were then evaluated using multivariate analyses. First, data ordination was visualized through non-metric Multi-Dimensional Scaling (nMDS). Then, diel (i.e., 24-h), and seasonal differences were tested according to the sampling design described above and a two-way PERMANOVA was run on the binomial deviance resemblance matrix of square-root transformed abundance data. Binomial deviance was selected as this is the most suitable distance to be used with species counts (Anderson and Millar, 2004), followed as well by pairwise comparisons between months. For both univariate and multivariate PERMANOVA tests, number of permutations was set at 9999 and "Permutation of residuals under a reduced model" was selected as permutation method.

The fish taxa contributing the similarities in each month, in both diurnal and nocturnal observations, and the average dissimilarities between pair of months were identified through SIMPER analysis. Differences between day and night for the most abundant species were also visualized through boxplots. Finally, fish diversity was estimated through Shannon-Wiener index (H'), and differences were tested by univariate PERMANOVA carried out on untransformed data and according to the sampling design described above.

All univariate and multivariate analyses were conducted using PRIMER6&PERMANOVA+ (Clarke and Gorley, 2006; Anderson et al., 2008).

2.5. Analysis of behavioural rhythms of most abundant species

A waveform analysis on the time series of counts of the 4 most abundant species (>2800 individuals recorded during the sampling period) was carried to assess the phase of their swimming rhythms (i.e., peaks timing and duration) (Chiesa et al., 2010). These species were selected because occurred all year round and were those characterizing each sampling period according to SIMPER results (see below).

In this analysis, all time-series were subdivided into 24-h segments (at 1-h sampling frequency) and a fluctuation was obtained by averaging all values of the different segments at the corresponding 1-h time intervals (Francescangeli et al., 2022). The resulting mean values (± standard errors) were plotted to determine the waveform' peaks and troughs.

The peak temporal amplitude was then computed according to the Midline Estimating Statistic of Rhythm (MESOR) method (Aguzzi et al., 2005), by re-averaging all waveform averages and the result presented as a threshold horizontal line superimposed onto the waveform plot (Refinetti, 2004). All mean values above the line defined the time limits of a significant increment in the visual counts. The onset and offset of activity were estimated by considering the first and the last values above MESOR, respectively, and because of the substantial variability, the activity was considered continuous if no >3 values occurred below the MESOR (Aguzzi et al., 2013). The waveform output plots' y-axis was not standardized to the same extent to make visible the mean counts fluctuations of the less abundant months, which would have otherwise been flattened. Plots were performed using the RStudio version 2023.09.1+494 (RStudio Core Team, 2023) with the package ggplot2 (Wickham, 2016).

2.6. Relationships of fish assemblage composition with environmental variables

Environmental data were tested for collinearity among variables by using a Draftsman's plot, with irradiance, turbidity, and direction of the wave data (Deg) being log-transformed to fit a linear distribution in. Only data with Pearson's correlation value <0.70 were retained for the analysis.

A Canonical Correspondence Analysis (CCA, Legendre and Legendre, 1998) was used to relate each species to environmental variables and then a second model was run considering also the month. Then, a DistLM (Distance-based multivariate multiple regression based on a linear model, Anderson et al., 2008) was used to assess which of the environmental variables influence fish assemblages' composition using “stepwise” as selection procedure and “AIC (Akaike Information Criterion)” as selection criterion. Three DistLM models were run, one for the overall assemblage and then two separate models for the day and night assemblages, respectively. The CCA was performed using the software PAST 4.10 (Hammer et al., 2001), while Draftsman's plot and DistLM models were run with PRIMER6&PERMANOVA+.

3. Results

The camera acquired 8672 videos equivalent to a total of 155.5 h of monitoring. From these recordings, 7802 videos (equivalent to ca. 117 h) were used for fish classification and counting, and the rest discarded (i.e., 870 videos, equivalent to 38.5 h) due to camera malfunctioning (e.g., camera shooting at light off, resulting in black footages) or high turbidity.

The accumulation curves, run for each season, showed that an average number of ca. 1900 videos per season were sufficient to mirror the species richness; however, an average number of 900 videos were enough to represent >91 % (on average) of the species richness per season (Suppl. Fig. 2).

3.1. Diel and seasonal changes in abundance, diversity, and assemblage composition

Out of the 83,138 individuals counted, 79,755 were observed during the day and 3383 during the night. Specimens of 24 different species belonging to 10 different families, and specimens belonging to the order Clupeiformes were identified. The family of Sparidae was the most representative one, including 12 of the 24 identified species.

Unidentified fish accounted for 66 % of the total individuals, 29 % of the remaining belonged to four species: the white seabream *Diplodus sargus* (18 %), the two-banded seabream *D. vulgaris* (5 %), the annular seabream *D. annularis* (4 %), and the bogue *Boops boops* (2 %) (Suppl. Table 1).

3.1.1. Diel and seasonal changes in fish abundance

An increase of fish abundance in warmer periods was observed from May to October (Fig. 2A). When examining day and night observations separately, higher fish abundance was observed during the day from May to October (Fig. 2B), while nighttime abundance was greater in June and from October to January (Fig. 2C).

The univariate PERMANOVA main test showed the presence of significant differences in fish abundance according to the factors: ‘month', ‘day/night', and for their interaction (all *p*-values<0.001) (Suppl. Table 2). The pair-wise comparisons for the factor ‘month' under pair of levels of factor ‘day/night' highlighted statistically significant differences (*p*-values≤0.05) between March/April, April/May, October/November, November/December for day samples, and from March to July and from August to November for night samples (Suppl. Table 3).

3.1.2. Day-night variations of fish assemblages' composition across seasons

The nMDS plot showed a clear segregation between day and night (Suppl. Fig. 3). When the nMDS plots carried out separately for day and night samples pointed out to different seasonal patterns of the fish assemblage (Suppl. Fig. 4). Indeed, while there was a seasonal separation of diurnal samples between those belonging to warmer seasons (spring and summer) from colder ones (winter and autumn), the night assemblages were more homogeneous, with a slender division between samples from February to September 2021, and those from October to February 2022. The univariate PERMANOVA main test showed significant differences in fish assemblages for the factors: ‘month', ‘day/night', and their interaction (all *p*-values <0.001) (Suppl. Table 4). Pairwise comparisons for the factor ‘month' under pair of levels of factor ‘day/night' highlighted statistically significant differences ($p \leq 0.05$) between March to May, and from September to January for day samples (Suppl. Table 5a), and from February to November 2021 and from August to November, and December/January for night samples (Suppl. Table 5b).

SIMPER analysis showed a variation by month of the species that mainly contributed to assemblage changes. Day samples showed *D. sargus* as the most representative species of the assemblage from March to July (95 % of contribution in March and April), *B. boops* in August and September, and *D. vulgaris* together with *Spondyliosoma cantharus* and *Spicara maena* from October to February 2022 (Suppl. Table 6). Night samples showed a similar species dominance, in August and September (*B. boops*) and from November to February (*D. vulgaris*). However, clupeoid fish were predominant from March to May (Suppl. Table 7).

Fish diversity, expressed as Shannon-Wiener (H′) index, was higher in summer and autumn than in the other two seasons, with the highest average H′ value observed from September to November (average 0.96 ± 0.47) (Fig. 3).

Univariate PERMANOVA test for H′ index showed significant differences ($p < 0.01$) in fish diversity for factors ‘month', ‘day/night' and for the interaction (Suppl. Table 8). Pair-wise comparisons within level

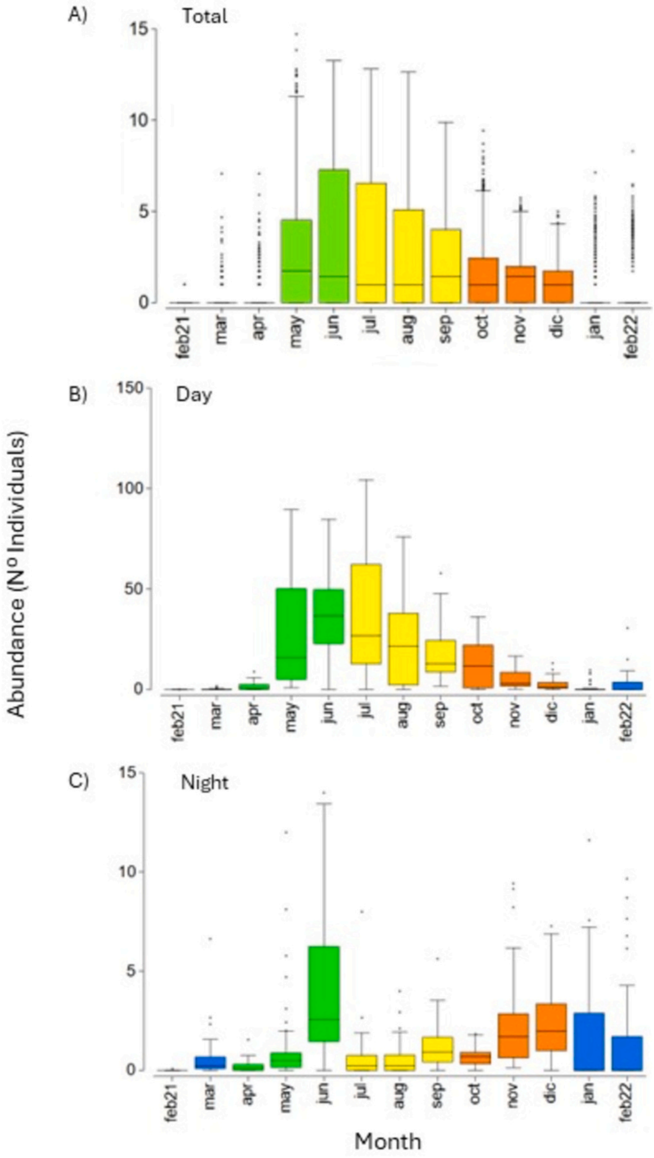

Fig. 2. Temporal patterns in fish abundance. Reported are: A) temporal changes in fish abundance (square-root transformed data). B) average fish abundance based on data collected during the day (untransformed data); C) average fish abundance based on data collected during the night (untransformed data). Colors represent the different seasons as it follows: GREEN: spring; YELLOW: summer; ORANGE: autumn; BLUE: winter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

'day' of factor 'day/night' under pairs of contiguous months showed significant differences ($p < 0.01$) between March to May and June/July, and from November to January (Suppl. Table 9). Pair-wise comparisons within level 'night' of factor 'day/night' for pairs of contiguous months showed significant differences ($p < 0.05$) from May to July, and from November to January ($p < 0.01$) (Suppl. Table 10).

3.2. Analysis of behavioural rhythms of most represented species

The waveform analysis showed the presence of a defined diurnal phase for the four most counted species (Fig. 4). The temporal development of that phase is reported across consecutive months for those species, and it remained diurnal with onset and offset adjustments according to the transient change in photophase (Suppl. Figs. 5 to 8). *Boops boops* showed a diurnal activity between 04:00 and 16:00. *Diplodus vulgaris* presented the maximum activity in August, with peak-time limits from 06:00 to 18:00. *Diplodus sargus* diurnal activity was higher between 6:00 and 18:00 during the winter-spring period, and between 4:00 and 18:00 during summer-autumn and showed the highest peak in July. Finally, *D. annularis* showed the maximum diurnal activity between 4:00 and 18:00 and the highest peak in July.

3.3. Relationships of fish assemblage composition with environmental variables

The current study has recorded one year of changes of different environmental variables during both day and night periods, including temperature, salinity, dissolved oxygen, chlorophyll-*a* (Chl-*a*), and irradiance. Temperature reached its maximum in August (27.6 °C). Salinity and Chl-*a* remained relatively stable throughout the year, with some exceptions during different seasons (the lowest value of salinity occurred in February, while maximum values for Chl-*a* were recorded in October and December). Dissolved oxygen experienced a decline in August, followed by a gradual increase until March. Lastly, lower levels of irradiance were found between October and January (Suppl. Fig. 9).

Based on the Draftman's plot output (Suppl. Fig. 10), the environmental auto-correlated variables (with correlation values $> \pm 0.7$) were eliminated. Therefore, current speed, wind speed (source of the height of the wave), direction of the wind origin (correlated with the direction of wind origin with respect to the North) and the percentage of oxygen saturation (correlated with the dissolved oxygen concentration) were not considered for the subsequent analyses.

The CCA plot highlighted a clear relationship between seasons and some of the environmental variables (Fig. 5), with factors conditioning fish counts that vary across seasons. Spring counts seemed to be mostly related to irradiance; records from summer were related to temperature and to the current direction; autumn counts were related to wind direction and turbidity, while winter samples were mostly related to water density and to dissolved oxygen concentration.

Regarding fish species (Fig. 5), the counts of *Diplodus annularis*, *Pagellus erythrinus*, *P. acarne*, *Boop boops*, *Serranus hepatus*, *Seriola dumerilii*, *Mullus surmuletus*, *Pagrus pagrus* and *Coris julis* appeared to be mostly linked to temperature, while that of species as *D. puntazzo*, *D. sargus*, *Dentex dentex* and *Sciaena umbra* was linked to irradiance. The counts of *Spondilyosoma cantharus*, *Scorpena porcus*, *Serranus cabrilla*, *Trachurus trachurus*, *Spicara fluxuosa*, *Mugil cephalus*, *D. cervinus* and Clupeiformes were instead more related to wind direction and turbidity. Moreover, these species were observed mainly during night recordings. Finally, the counts of *D. vulgaris*, *S. maena*, *Chromis chromis* and *Oblada melanura* were more correlated to density and dissolved oxygen concentration.

The DistLM output indicated that the best explanatory variables of the whole fish community were irradiance, salinity, and temperature, explaining together 43.4 % of the total variance. All these variables were statistically significant ($p \leq 0.05$). The variance of the diurnal community was mainly explained by temperature (17.1 %), and Chl-a concentration (4.8 %), a proxy of trophic status (Suppl. Table 11) (both $p < 0.05$). The other variables contributed <4 % to the total variance and were not significant (Suppl. Table 11).

4. Discussion

In this study we propose the design and use of a cabled video-observatory connected to an inactive off-shore gas platform, to investigate the fish assemblage.

This study enabled us to identify the seasonal cycles in species abundance and composition and the species replacement during nictemeral shifts, with special reference to the four most abundant species. The data collected using this observatory were related to the main oceanographic variables via a multiparametric video-synchronous data collection. Overall, the continuous presence of rig-associated species (i.

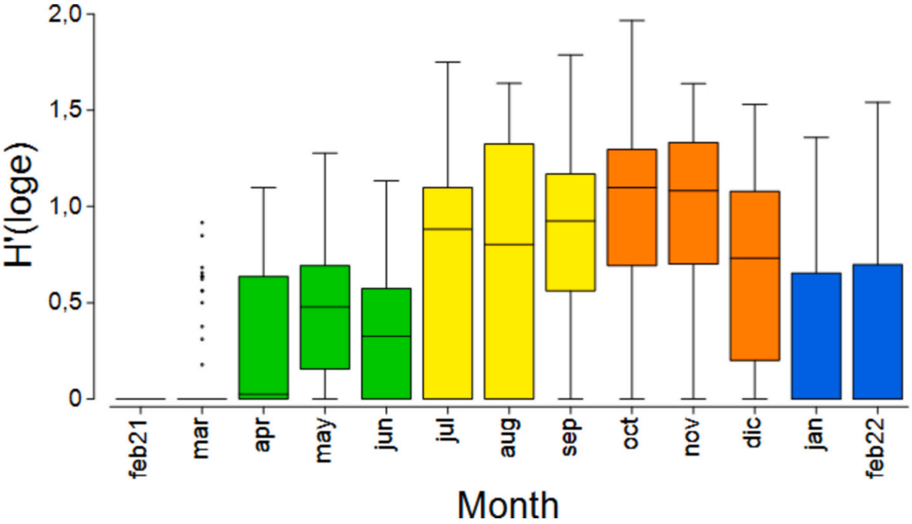

Fig. 3. Boxplot of the fish diversity by month, based on Shannon Index (H′). Colors indicate the different seasons: GREEN: spring; ORANGE: summer; YELLOW: autumn; BLUE: winter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

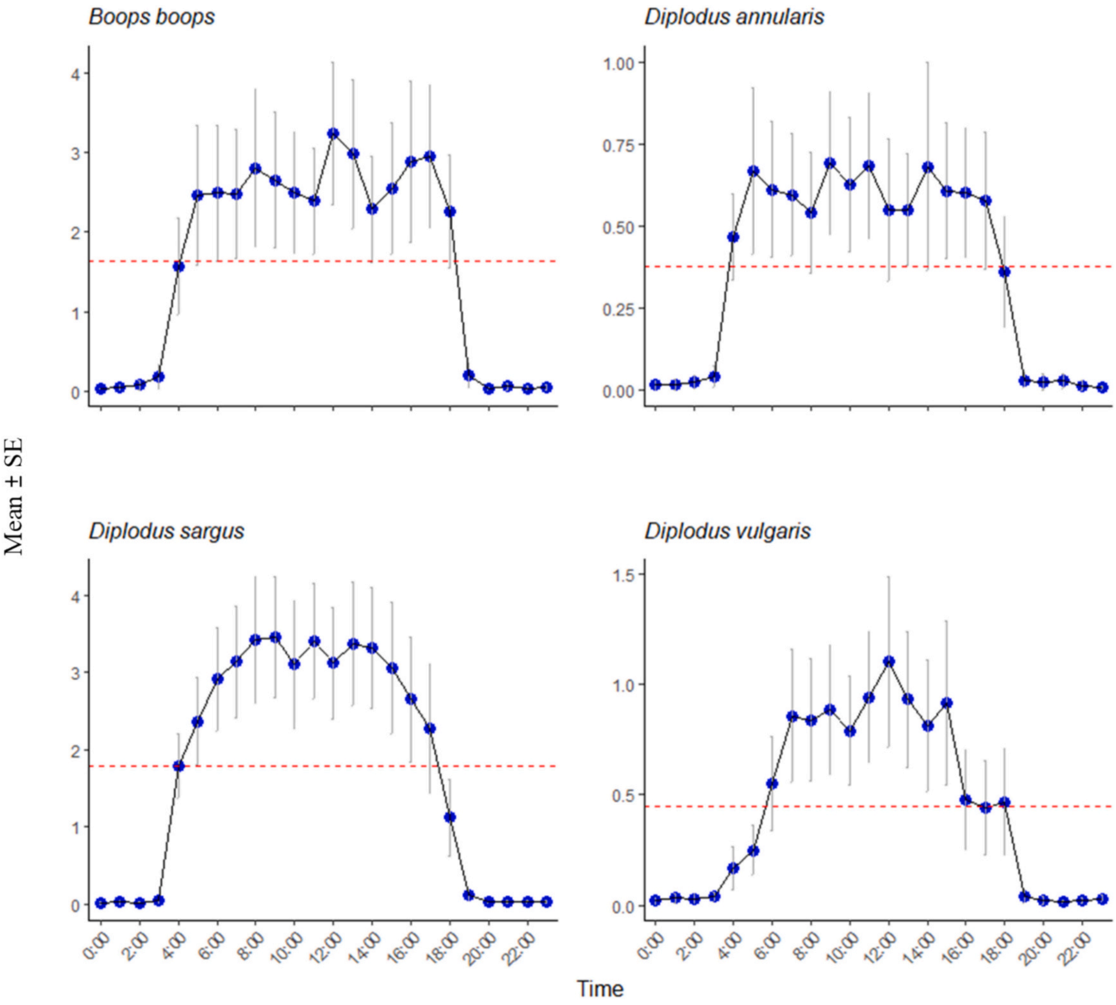

Fig. 4. Waveform analysis output (mean ± SE) for time series of *Boops boops*, *Diplodus sargus*, *D. annularis* and *D. vulgaris* counts (note the different scale) obtained during 1 year of continuous video monitoring. The phase of counts time series is identified by values above the MESOR (the red dash line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

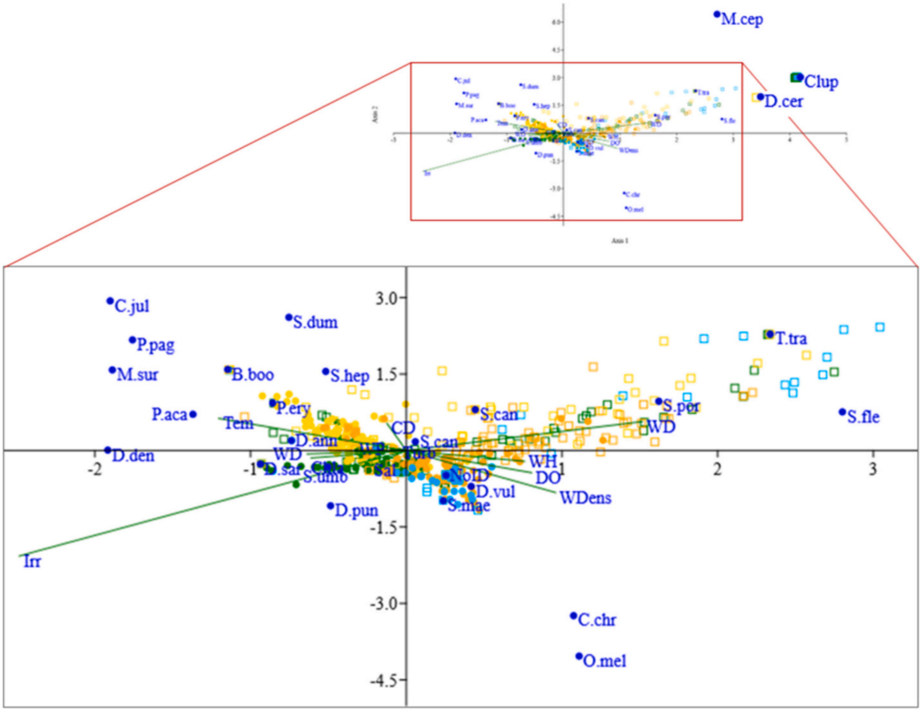

Fig. 5. CCA output for the analysis of species counts temporal response upon some environmental variables combined with the month factor (environmental variables are vectors). Colors indicate the different seasons: GREEN: spring; ORANGE: summer; YELLOW: autumn; BLUE: winter. Dots represent day samples, while squares represent night samples. WH = Wave height (m); WP = Wave period (s); WD = Wave direction (Deg); CD = Current direction (Deg); WD = Wind direction (Deg); Irr = Irradiance (W/m^2); Temp = Temperature (°C); Sal = Salinity (PSU); WDens = Water density (Kg/m^3); DO = Dissolved oxygen (ml/l); Chl-a = Chlorophyll-a concentration (ug/l); Turb = Turbidity (NTU). Acronyms of species correspond to: *Diplodus annularis* (D.ann), *Pagellus erythrinus* (P.ery), *P. acarne* (P.aca), *Boop boops* (B.boo), *Serranus hepatus* (S.hep), *Seriola dumerilii* (S.dum), *Mullus surmuletus* (M.sur), *Pagrus pagrus* (P.pag), *Coris julis* (C.jul), *D. puntazzo* (D.pun), *D. sargus* (D.sar), *Dentex dentex* (D.den), *Sciaena umbra* (S.umb), *Spondilyosoma cantharus* (S.can), *Scorpena porcus* (S.por), *Serranus cabrilla* (S.cab), *Trachurus trachurus* (T.tra), *Spicara fluxuosa* (S.fle), *Mugil cephalus* (M.cep), *D. cervinus* (D.cer), *D. vulgaris* (D.vul), *S. maena* (S.mae), *Chromis chromis* (C.chr) and *Oblada melanura* (O.mel). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

e., *Diplodus* spp.) and other bentho-nekton species (i.e., *Scorpaena* spp. and *Serranus* spp.) indicated that the offshore platform is acting as a Fish Aggregating Device (FAD). This confirms the role of offshore infrastructures as shelter and food providers for fishes, locally increasing their richness and diversity (Fabi et al., 2002; Scarcella et al., 2011a). Although previous investigations already highlighted the role of offshore platforms in influencing fish communities in the Adriatic Sea (Fabi et al., 2004; Andaloro et al., 2011; Consoli et al., 2013; Tassetti et al., 2020), this is the first temporally intensive (i.e., hours), continuous (from day-night to seasonal scales), and long-lasting (13 months) monitoring study on fish changes associated with an offshore platform in relation with several environmental drivers.

4.1. Nictemeral and seasonal changes in fish abundance and community composition

In the present study, a higher fish abundance was found in late spring and summer. These results corroborate previous findings that indicate a higher abundance of most of the identified fish species in summer, and lower in winter months (Aguzzi et al., 2020a, 2020b). Along the Mediterranean coast, fish abundance usually shows “intermediate” levels in autumn and spring, as they are considered transitional periods in fish-assemblage composition (Santos et al., 2005). The lowest abundances were observed from January to April. This pattern is consistent with that observed for the pelagic fish in the Mediterranean and in the Central Adriatic Sea and is most likely driven by changes in temperature (Duli et al., 2005). Indeed, during winter in the Northern and Central Adriatic basin, the water temperature drastically drops to ca. 8–10 °C (Artegiani et al., 1997), causing most of the species to migrate towards deeper and warmer waters (Bombace, 1992). Consistently, in the current study the lowest temperatures (ca. 10 °C) were recorded in January and February, together with the lowest fish abundance. To a certain extent, nictemeral changes of marine fish abundance and composition reflect habitat use and the species-specific activity (Arrington and Winemiller, 2003).

At the assemblage level, 12 species were identified over one-year period, with significant differences in their occurrence and abundance at both diel and seasonal levels. The multivariate analyses showed the existence of a seasonal pattern in nictemeral changes, with a separation of diurnal samples between those belonging to warmer seasons from colder ones; and night assemblages being more homogeneous through the seasons. Fish assemblage composition varied consistently between day and night monitoring, with a marked decrease in both abundance and species richness during the night, accordingly with previous observations along north-western Mediterranean coasts, although carried out using different methodological tools (Azzurro et al., 2007; Santamaria et al., 2013; Hayward and Ryland, 2017). The observations collected during the day were more dispersed, diverse (i.e., encompassing a greater number of species than night one), and showed more pronounced seasonal fluctuations. Some species (*Diplodus sargus*, *D. vulgaris and Boops boops*) dominated in terms of abundance contributing between 60 % and 95 % to the overall assemblage composition, in contrast with the results obtained by Aguzzi et al. (2020b) in Croatia (on the eastern side of the Adriatic Sea) in which the predominant species did not exceed 50 %.

The Shannon index indicated a higher diversity in the fish assemblage during autumn, an intra-annual variation that is considered a reliable proxy for seasonal patterns of changes in local fish abundance (Condal et al., 2012). The high value of diversity of the day samples during July was mostly due to the presence of individuals of *D. sargus*. The community assemblage was characterised by a seasonal turnover as revealed by sample separation between the winter/spring and the summer/autumn period. Furthermore, nocturnal samples displayed a lower species diversity than diurnal ones, as reported in other Mediterranean ecosystems not influenced by the presence of artificial infrastructures (Aguzzi et al., 2013).

4.2. Analysis of behavioural rhythms of most represented species

The waveform analysis showed that the four dominant species displayed seasonal fluctuations with a diurnal phase. The bogue *B. boops* showed an increase lasting several months in summer season, probably explained by its gregarious behaviour and the long-spawning period (Dobroslavić et al., 2017) that, at least in the Adriatic Sea, occurs from January to May. Differently, the white seabream *D. sargus* and the annular seabream *D. annularis* showed a more defined increase in July. Similarly, *D. sargus* counts peaked in July as were correlated with daily photoperiod. Interestingly, the results reported here show a different temporal pattern than the one reported using the OBSEA observatory for *D. sargus*, nor for *D. annularis* (Condal et al., 2012; Aguzzi et al., 2015). At OBSEA white sea bream rhythms peaked in June and annular seabream counts significantly increased during autumn/winter months. The white seabream shows a unique seasonal spawning, which occurs in the Western Mediterranean between March and June (www.fishbase.org, version 02/2022). Probably, the summer aggregation behaviour found in this study was related to other factors than reproduction, possibly linked to the fluctuations in prey availability (Pallaoro et al., 2006). Artificial reefs, like offshore platforms, have been demonstrated to be important feeding sites for the omnivorous *D. sargus*, which mainly feeds on bivalves, echinoderms, and algae (Sala and Ballesteros, 1997). Thus, the artificial reef could probably be used as a foraging ground, supporting individuals' dietary requirements, just before the onset of their spawning period.

Summer aggregations of *Diplodus annularis* are instead associated to reproduction, as in fact the spawning period for this species in the Adriatic Sea is between June and August (www.fishbase.org, version 02/2022). Accordingly, the greater abundance of *D. annularis* in our study was found during these months.

The two-banded sea bream *D. vulgaris* showed a temporally more scattered pattern, starting to appear around April and then the abundance displayed sparse peaks over the year, with the highest one in October. The delayed appearance can be justified by the community's disruption during the observatory's assembly, and its adaptation to the new structure may had taken several months. The spawning season occurs in January and December but the increase of their abundance in October could be related to the dietary requirements for reproduction (Sbragaglia et al., 2018).

4.3. Relationships of fish assemblage composition with environmental variables

Temporal variations in the fish assemblage associated to the offshore platform were related with different environmental variables. Species' list and their abundance indicate the occurrence of marked swimming rhythms potentially associated to solar-light intensity and photo-phase length (respectively, for day-night and seasonal controlled rhythms) and to water temperature (Vinagre et al., 2016; van der Walt and Fitchett, 2021). Light and temperature, indeed, deeply influence fish presence/absence and affect species' physiological performance (Day et al., 2018), also controlling dissolved oxygen concentration in the water column (Lipizer et al., 2014), as evident also in our study. Climate change is undoubtedly altering these physicochemical parameters in the Mediterranean Sea, including temperature (Soto-Navarro et al., 2020). These changes can contribute to modify fish assemblage composition and distribution, including shifts in natural communities (Hellmann et al., 2008; Albouy et al., 2012; Valente et al., 2023). Long-term monitoring systems like SMS may be useful to understand assemblage composition responses to environmental drivers at regional level, and to construct baselines for projection models such as Species Distribution Modelling (Schickele et al., 2021) or Species Temporal Turnover (Albouy et al., 2012) under future climatic projections. Moreover, the continental shelf of the North and Central Adriatic Sea, by hosting >100 offshore platforms (Maggi et al., 2007), can offer a leverage for the creation a large-scale network of continuous monitoring systems, providing useful information of changes in fish assemblage composition which can help to properly manage biological resources across the Adriatic Sea.

5. Conclusion

Our findings highlight the scientific potential of the re-use of offshore platforms as underwater ecological observatories enabling fish monitoring and providing complementary information to that collected using traditional sampling techniques (e.g., visual census, use of trammel nets or other fishing techniques). The use of underwater cameras allows the monitoring of fish assemblages at high-frequency and over the long term, opening new opportunities for investigating the biological rhythms of different species. Advances along this technological path can provide novel and effective monitoring tools for environmental assessment of marine ecosystem in the context of European management policies like the MSFD (EC 2008/56), or the expansion of a global observatory system as invoked by the Ocean Decade 2024, that have already accepted high-definition cameras as a promising approach for monitoring the marine environment, specifically regarding the MSFD Descriptor 1: 'Biodiversity', Descriptor 2: 'Non-indigenous species', Descriptor 3: 'Commercial fish and shellfish', Descriptor 4: 'Food webs and related indicators'. The results obtained from observations made by SMS observatory will allow also gathering information to complement other ongoing monitoring initiatives using permanent observatories in the Mediterranean Sea (i.e., OBSEA www.obsea.es and SubEye https://imedea.uib-csic.es/sites/sub-eye/home/ in Spain; Šibenik Natura 2000 in Croatia https://www.irb.hr/eng/News/Live-Web-Cams-at-the-Martinska-Bay; and Acqua Alta in Venice Lagoon https://www.ismar.cnr.it/en/infrastructures/oceanographic-infrastructures/acqua-alta-tower/) and in the Atlantic (i.e., SmartBay in Ireland: https://www.smartbay.ie/; Molene in France: https://www.emso-fr.org/EMSO-Molene. Underwater ecological observatories can be used as continuous long-term monitoring sites for different environmental and biological variables, which are highly useful to understand local dynamics of fish assemblages' composition within a particular area. Due to the high number of offshore platforms in the Adriatic Sea, the creation of network of observatories can be highly beneficial for environmental management and species conservation. Finally, the ongoing and future developments of such observatories, integrating automatization (Artificial Intelligence and Deep Learning) processes for species counting and identification or *in situ* eDNA sampling and processing (Pawlowski et al., 2022), could further expand their potential to be used in marine monitoring at large spatial and temporal scale.

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CRediT authorship contribution statement

E. Fanelli: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **P. Masia:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **A. Premici:** Writing – review & editing, Formal analysis, Data curation. **E. Volpato:** Formal analysis, Data curation. **Z. Da Ros:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **J. Aguzzi:** Writing – review & editing, Methodology, Formal analysis. **M. Francescangeli:** Writing – review & editing, Formal analysis. **A. Dell'Anno:** Writing – review & editing, Resources, Project administration, Funding acquisition,

Conceptualization. **R. Danovaro:** Writing – review & editing, Funding acquisition, Conceptualization. **R. Cimino:** Resources, Project administration. **F. Conversano:** Writing – review & editing, Resources, Project administration, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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