Marine Pollution Bulletin 221 (2025) 118504

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

A multi-faceted approach to assess the sustainability of diving tourism: The case of Rome's MPA

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ARTICLE INFO

Keywords:
MPA
Scuba diving
Coralligenous habitat
Bio-indicator
Impact
Tourism management

ABSTRACT

Marine Protected Areas (MPAs) are crucial for conserving biodiversity, ensuring the sustainable use of marine resources, and hosting most diving destinations. Several studies show that diving activities can damage marine life. The present study aimed to assess the disturbance of SCUBA diving activities within the Secche di Tor Paterno MPA through a multi-faceted approach. We considered three levels of analysis. Firstly, to identify the factors influencing the number of diver-substrate interactions, we analysed frequentation of the MPA, behaviour and profiles of visiting divers. Additionally, we identified the hotspots, i.e., the areas most subject to physical disturbance, through small-scale spatial analysis. Finally, we analysed the potential impacts of diving tourism on the structure of benthic communities, using bio-indicator organisms sensitive to such disturbances. A moderate level of frequentation was reported. The mean interaction rate was quantified as 0.13 interactions min^{-1}, influenced primarily by diving experience and camera use. Only 1 % of these interactions were recorded as physical damage to benthic organisms. The hotspots coincided with areas attractive to underwater photographers. Despite various diver-substrate interactions, no significant changes in bio-indicator species diversity were observed, confirming depth as the most significant factor explaining the variations in benthic community diversity among dive sites. The multi-faceted approach used in this study provided a comprehensive view of touristic diving disturbance in the MPA, serving as a starting point for improving interventions and conservation strategies in an adaptive management framework.

1. Introduction

Marine Protected Areas (MPAs) are spatially defined regions reserved by legislation or other effective means, aimed at ensuring a higher level of protection for the marine environment than surrounding areas. MPAs are a crucial tool for conserving marine ecosystems, contributing to increasing biodiversity and biomass, preventing habitat loss, maintaining key species, and ensuring ecological balance. The conservation outcomes of MPAs and the health status of marine resources are connected to socio-economic benefits by supporting sustainable fisheries, recreational boating, and tourism activities (Sala et al., 2013). To balance conservation outcomes with anthropic use, MPAs are typically divided into management zones with different levels of protection, based on the permitted activities. Zoning of MPAs includes: fully protected areas, where no anthropic activities are permitted; general reserve zones, where low-impact recreational uses (e.g., boating, snorkeling, fishing, SCUBA diving) are permitted under strict management control; and minimally protected areas where also extractive or destructive activities (e.g., recreational and artisanal fishing) are managed, and often serve as buffer zones between highly protected areas and surrounding unprotected marine regions (Grorud-Colvert et al., 2021). The anthropic activities permitted within an MPA can be a potential source of impact for marine habitats. Therefore, continuous ecological assessments are necessary to sustain conservation and benefits to society (Dunham et al., 2020).

SCUBA diving tourism is one of the largest sectors in the ocean economy, supporting regional economies by generating revenue and employment (Schuhbauer et al., 2023). As with other types of marine tourism, SCUBA diving tourism may contribute to increasing public awareness of marine ecosystems and their conservation (Schuhbauer et al., 2025). According to a recent study, 70 % of the 33.1 million scuba dives that occur annually in marine environments worldwide take place

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https://doi.org/10.1016/j.marpolbul.2025.118504
Received 13 May 2025; Received in revised form 11 July 2025; Accepted 24 July 2025
Available online 4 August 2025

within MPAs (Cabral et al., 2025). The "MPA name effect" highlights how divers' attraction to dive sites within protected areas can generate economic opportunities for the sustainability of MPAs and underscores the need to expand the global MPA network to encompass all dive sites worldwide (Viana et al., 2017). The effective management of diving tourism is crucial in evaluating whether its positive effects outweigh the potential impacts of this activity (Giglio et al., 2020). Indeed, SCUBA diving activities, particularly at highly frequented sites, can harm marine life. Direct disturbances, such as physical contact with organisms that can potentially displace, break, or kill them, and spread diseases, as well as indirect disturbances like sediment resuspension, air bubble release, and human presence altering animal behaviour, threat marine community structure (Chung et al., 2013; Lamb et al., 2014; Zakai and Chadwick-Furman, 2002).

The organisms most affected by the disturbance associated with SCUBA diving activities, as well as their potential damaging effects, are habitat-forming species (e.g., anthozoans, bryozoans, ascidians). They are susceptible to SCUBA diver interactions due to their fragile skeletal components and erect morphologies (Zakai and Chadwick-Furman, 2002; Casoli et al., 2017). The exposure of these sessile species to intensive SCUBA diving activities may increase their vulnerability to predation and disease, as well as compromise their growth (Lamb et al., 2014; Guzner et al., 2010). Cumulative effects can extend to the community level, leading to a shift in community state, favouring erosion-resistant encrusting and massive species. This shift can reduce the structural complexity of the communities, resulting in a decrease in their resilience to other types of disturbances, such as the synergistic effects of climate change (Lyons et al., 2015; Zentner et al., 2023). Moreover, habitat-forming species are absent from disturbed communities, resulting in a reduction in aesthetic value, ultimately causing a detriment to global coastal economies (Giglio et al., 2020; Forrest et al., 2023).

In the Mediterranean Sea, studies addressing the impacts of SCUBA diving activities have focused mainly on the coralligenous reefs (Sala et al., 1996; Garrabou et al., 1998; Coma et al., 2004; Di Franco et al., 2009; Linares et al., 2010; Luna-Pérez et al., 2010; Nuez-Hernández et al., 2014; Terrón-Sigler et al., 2016; Casoli et al., 2017; Betti et al., 2019, 2023; Giglio et al., 2025). These studies identified several species belonging to the taxa of ascidians, bryozoans, and corals, which have shown cumulative effects of diving-related damage, including reductions in organism abundance, body size, and colony size. Among these species are: the erect bryozoans *Adeonella calveti* Canu & Bassler, 1930, *Reteporella* spp. (Busk, 1884), *Smittina cervicornis* (Pallas, 1766), *Myriapora truncata* (Pallas, 1766), *Pentapora fascialis* (Pallas, 1766), *Frondipora verrucosa* (Lamouroux, 1821); the anthozoans *Cladocora caespitosa* (Linnaeus, 1767), *Leptopsammia pruvoti* Lacaze-Duthiers, 1897, *Eunicella cavolini* (Koch, 1887), *Eunicella singularis* (Esper, 1791) and *Paramuricea clavata* (Risso, 1827); and the erect ascidian *Halocyntia papillosa* (Linnaeus, 1758). Their sensitivity to diving disturbance, ease of recognition and readily measurable distribution make these species valuable bio-indicators for assessing the impact of diving activities (Luna-Pérez et al., 2011).

Previous studies have assessed diving activities and their potential effects on benthic communities using two approaches: the evaluation of the profile (i.e. sex, experience, diving certification, and use of camera) and behaviour of visiting SCUBA divers in relation to their interactions with seabed (Di Franco et al., 2009; Luna et al., 2009; Giglio et al., 2016; Lucrezi et al., 2019; Balzaretti-Merino et al., 2021) Lucrezi et al., 2021; McBride, 2021), and the analysis of species sensitive to disturbance and their potential temporal and spatial changes due to SCUBA diving activities (Garrabou et al., 1998; Zhang et al., 2016; Casoli et al., 2017; Betti et al., 2019). However, focusing on a single perspective when assessing the SCUBA diving disturbance does not provide a comprehensive understanding of the issue, potentially leading to the adoption of incomplete and/or ineffective management actions.

The present study aimed to assess the disturbance of recreational SCUBA diving activities within the Secche di Tor Paterno MPA of Rome through a multi-faceted approach. The first component of the study focused on analysing the frequentation patterns of the MPA, the profile and behaviour of the visiting SCUBA divers. This step allowed for the quantification of SCUBA diving disturbance and the identification of the factors that most influenced the number of diver-substrate interactions. Additionally, the data collected during SCUBA dives enabled the identification of seabed areas most subjected to physical disturbance through small-scale spatial analysis. Lastly, the activities allowed for a detailed analysis of the potential impacts of SCUBA diving tourism on the composition and structure of the benthic communities in the MPA, using bioindicator organisms recognized as sensitive to such disturbances.

2. Materials and methods

2.1. Study area

The study was carried out at the Secche di Tor Paterno MPA located in the central Tyrrhenian Sea, approximately 12 km off the coast of Rome (Fig. 1): it comprises a single general reserve zone. The MPA is the only one fully submerged within the Mediterranean Sea that does not border any coastal regions. The seabed is characterized by Pleistocene sedimentary rocks that form a shoal extending approximately 70 ha, surrounded by soft substrates and rising from a depth of 50 m to the shallowest point of 18 m (Ardizzone et al., 1998; Albano and Sabelli, 2012). The MPA is located to the south of the Tiber River estuary, whose presence has a substantial influence on the ecosystems within the MPA as well as in the surrounding marine environments. Indeed, the Tiber River discharges a considerable influx of freshwater, sediments, and organic matter into the coastal system, influencing water visibility and consequently photosynthetic process, nutrient availability, and the food supply for filter-feeding communities (Ardizzone et al., 2018; Varghese et al., 2024).

The MPA hosts the seagrass *Posidonia oceanica* L. (Delile, 1813), which occurs from the top of the shoal down to a depth of 30 m, colonizing the hard substrates in sparse patches and forming small meadows in the sedimentary pools (Albano and Sabelli, 2012). Coralligenous reefs extensively cover the rocky seabed in the deeper areas of the shoal, while co-occurr with the seagrass patches at shallower depths (Ardizzone et al., 2018). These two ecosystems are endemic to the Mediterranean Sea and protected by several EU regulations and pan-Mediterranean agreements and protocols. *Posidonia oceanica* meadow and coralligenous reefs offer humans with provisioning, regulating, and cultural ecosystem services (Zunino et al., 2020). Additionally, their ecological role and aesthetic value enhance the enjoyment of underwater recreational activities, making them highly valued by SCUBA divers (Tribot et al., 2016).

The Secche di Tor Paterno MPA was established in 2000 and is currently managed by the Regional authority RomaNatura. SCUBA diving tourism is only permitted if supervised by the authorized diving centres, within a 100-m radius area from the mooring buoys with a maximum of 12 divers *per* dive, and exclusively for holders of an Advanced Open Water Diver certification or higher due to the depth of the shoal. Pre-dive briefings to highlight the importance of low-impact behaviour are mandatory. Additionally, the management authority establishes a scheduling calendar to manage the use of the diving sites and requires authorized diving centres to annually report data on SCUBA dives performed within the MPA. This system ensures that the maximum permitted number of SCUBA dives at the various sites is not exceeded and allows equitable access for every authorized Diving center. In 2023, touristic diving activities were permitted in five SCUBA diving sites, marked by mooring buoys (Fig. 1; Table S1).

2.2. Data collection

2.2.1. Frequentation of the MPA and use of dive site

Assessing the potential impacts of diving activities in the Secche di

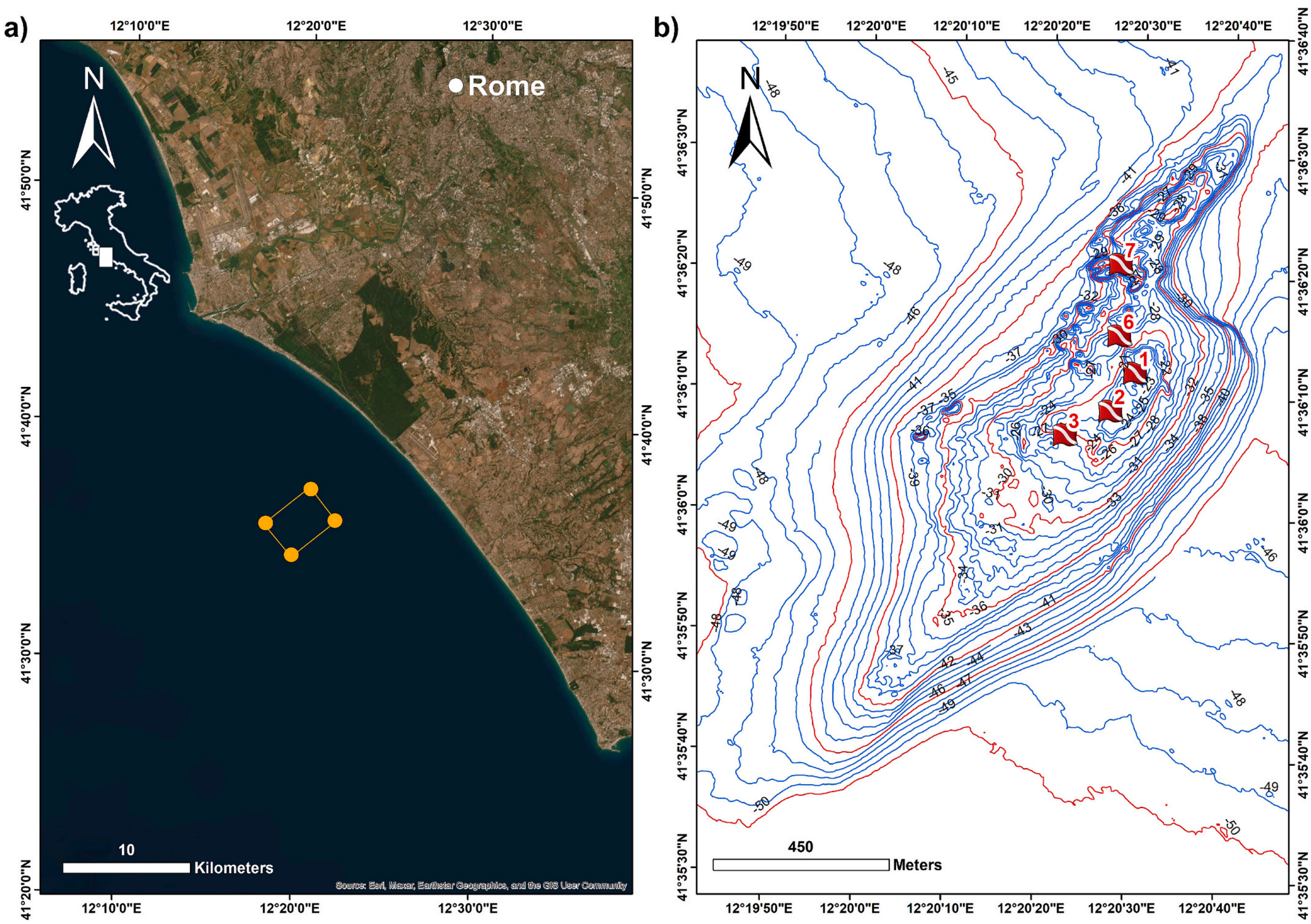

Fig. 1. The study areas maps show the location and boundaries of the MPA of Rome Secche di Tor Paterno (orange rectangle in the panel a), and the morpho-bathymetric features of the seabed (panel b) in the proximity of the mooring buoys where diving activities are permitted. Mooring buoys are identified by "Diver down flag" and named as the corresponding dive site: 1, 2, 3, 6, and 7.

Tor Paterno MPA first required quantifying the total annual number of dives and use of dive sites. To this goal, the official registers compiled by the diving centres and provided by the management authority were consulted. The frequentation of the MPA was estimated by calculating the total annual number of dives from 2003 to 2023. Additionally, the use of dive sites was assessed as the percentage of dives at each site carried out both in 2022 and 2023.

2.2.2. *SCUBA diver behaviour and profiles*

Data on divers' behaviour and profiles were collected through direct observations of SCUBA divers during 20 dives from May to October 2023. Observers sampled an average of 4 divers at a time, recording their with the bottom and the benthic organisms. The observers joined the group and maintained a discreet presence throughout the dive in order to minimize the potential impact on the divers' conduct. Throughout the monitoring period, only three divers were surveyed twice, and during the second sampling, they were conscious of being observed to gather data on their diving behaviour. Each sample period began when divers approached the seabed and ended at the time they began ascent to the surface. Divers were followed from a distance of 3–4 m. The diver-substrate interactions were recorded on a PVC slate and categorized as either contact or physical damage, with the latter occurring when harm to the benthic organisms (i.e., detaching part or the entire organism) was observed. We reported the depth and time at which diver-substrate interactions occurred: the time was then categorized as dive phase (i.e., start, middle, or end) equally dividing the time spent underwater since all dives had a comparable duration of 35–40 min. Furthermore, we recorded the specific body parts or equipment that contact the seabed: fin, knee, hand, camera, and scuba gear (i.e., buoyancy compensator devices, regulators, compass, or tank). The taxa affected by the interaction were recorded and grouped in two morphological categories: (a) organisms structuring the erect layer (i.e., the gorgonians *E. cavolini*, *E. singularis,* and *P. clavata*), and organisms belonging to the basal and intermediate layer (i.e., crustose coralline algae, encrusting and erect bryozoans), following the subdivision of coralligenous layers provided by Gatti et al. (2015).

After the dive, the following data about SCUBA divers' profiles were collected through anonymous interviews with the entire diving group: gender, experience (i.e., the total number of dives completed during the lifetime, grouped in four categories: 0–50; 51–100; 101–500; > 500), diving certification (Advanced Open Water; Rescue; or Dive Master), and use of camera.

We requested divers to provide verbal consent for the inclusion of their data in the survey.

2.2.3. *Identification of the most affected areas (hotspots)*

To identify the areas of the seabed most affected by diver-substrate interactions and provide a spatial explicit tool to guide the management of touristic activities within the MPA, we reconstructed the route taken by the group of divers at the end of each dive. This was based on an assessment of the seafloor morphology using the AMP high-quality digital terrain model (DTM, 50 × 50 cm grid size, provided by the management authority), the depths at which diver-substrate interactions occurred, and the supervision of the diving centres' guides that know each site. The use of predetermined dive routes, constant divers' swimming speed, and comparable dive durations of 35–40 min allowed the reconstruction with acceptable approximation. Each route was digitalized and georeferenced using the geographic information system (Q-GIS): dive routes were aggregated into a single vector file (i.e., line shapefile) and classified according to the date and the mooring buoy from which the dive started. Then, each route was divided into eight segments, each corresponding to a 5-min interval of the dive. The total number of diver-substrate interactions within each segment was quantified according to the minute of the dive when the interaction occurred and expressed as the number of interactions min^{-1}.

2.2.4. Effects on benthic communities

To investigate the potential effects of SCUBA diving tourism on benthic communities' structure, we adopted a BACI sampling design (Before/After and Control/Impact; Underwood, 1992). We considered four sampling sites, distributed across two depth layers: two shallow sites (19–24 m) and two deep sites (30–32 m). Within each depth range, the two sites were classified according to the variable condition: frequented site, visited by SCUBA divers as located within a 100-m radius of the mooring buoy, and unfrequented site, serving as a control, positioned tens of meters beyond the 100 m radius of the mooring buoy. At each site, three replicate stations were sampled, approximately ten meters apart, for a total of 12 sampling stations within the MPA. Scientific SCUBA divers acquired a total of 10 images *per* station, each measuring 50 × 40 cm (0.2 cm^2), within a 4 m^2 area on vertical substrates characterized by coralligenous reefs. The image acquisition was carried out before (May-early June 2023) and after (late September-early October 2023) the peak of the touristic diving season, respectively. Photographs were taken by using a Canon 5D Mark IV camera in an Aquatica Digital housing equipped with INON Z-330 strobes and two laser pointers (spaced 10 cm) for scale reference. The lens was kept as parallel as possible to the substrate to reduce parallax errors. Photographic analyses were subsequently performed using the photoQuad software (Trygonis and Sini, 2012). A 100-cell grid was superimposed on the 0.2 cm^2 image area, and the frequency of occurrence was estimated for the following 12 taxa, considered as bio-indicators of the impact of SCUBA diving activities: the erect bryozoans *A. calveti*, *S. cervicornis, M. truncata*, *F. verrucosa, P. fascialis*, and *Reteporella* spp.; the anthozoans *C. caespitosa*, *E. cavolini*, *E. singularis*, *L. pruvoti*, and *P. clavata*; the erect ascidian *H. papillosa*.

2.3. Statistical analyses

To investigate patterns in diver-substrate interactions in the MPA, we first analysed the possible observer effect on SCUBA divers' behaviour. We used the Wilcoxon-Mann-Witney test to assess whether the number of diver-substrate interactions significantly changed between the first and second sampling events for the three divers that were observed twice. Afterward, Multiple Correspondence Analysis (MCA) was used to examine the relationship between the categorical variables defining SCUBA divers' profile, with a focus on identifying those that increased the number of diver-substrate interactions. The following qualitative variables were considered: gender, experience, diving certification, and use of camera. A Chi-squared test was conducted to further explore the potential dependence between variables. Moreover, the Wilcoxon-Mann-Whitney test and Kruskal-Wallis test were used to assess differences in the number of diver-substrate interactions among the levels of qualitative variables considered in the MCA and among dive phases (start, middle, and end), followed by Dunn's test for pairwise comparisons.

Multinomial test was used to determine if interactions preferentially occur with a specific body part or piece of equipment, analysing whether the observed proportions across different categories matched the expected proportions based on a theoretical distribution.

To provide a map of portions of the seabed most affected by diver-substrate interactions, we used Kernel Density Estimation (KDE) to create a modelled surface based on the centroid of each segment constituting the dive route. Each centroid was quantified with the number of interactions min^{-1} that occurred in that specific segment. A kernel density function was used to fit a smooth curve over each centroid in Q-GIS (UTM projected coordinate system WGS 1984 Zone 33 N) with a search radius set to 10 m. The search radius selection was based on the average visibility conditions during the samplings. The output cell size (resolution) was 1 m.

A Principal Coordinates Analysis (PCoA) based on Bray-Curtis dissimilarity was performed on frequency data of the bioindicator species obtained through image analysis. The observations on the PCoA biplot were visualized according to condition (frequented and unfrequented), depth layers (deep and shallow), and time of sampling (before and after peak of the diving season).

We quantified the α-diversity of the assemblage at the sampling station level by using Tsallis entropy (H_q). Tsallis entropy can be defined as the amount of uncertainty calculated from the frequency distribution of species in a community (Furuichi, 2005): in this study, we used the bioindicator species exclusively. The entropy measure can be converted into a diversity measure, or Hill numbers, through the deformed exponential transformation e_q of the Tsallis entropy (Marcon et al., 2014). The parameter q within the Tsallis entropy calculation allows tuning H_q in terms of the importance given to rare species. We analysed α-diversity as a function of the order q, in relation to depth layers, condition, and time of sampling to obtain easy-to-interpret patterns of diversity. We selected the diversity order of $q = 0$, $q = 1$, and $q = 2$, which correspond to the species richness, the Shannon index, and the inverse of Simpson's index, respectively. Then, we estimated three models on α-entropy: for $q = 0$, we estimated a General Linear Model (GLM) with negative binomial distribution, for $q = 1$ a Linear Model (LM) with Gaussian distribution, and for $q = 2$ a GLM with Gamma distribution, respectively. In all models, we used depth layers, condition, and time of sampling as explanatory variables, considered as interacting factors.

All tests were performed at a significance level of $p < 0.05$. All the statistical analyses were performed in the R platform (version 4.3.2).

3. Results

3.1. Frequentation of the MPA and use of dive site

According to the official registers provided by the MPA's management authority, the frequentation since its establishment is 2424 ± 513 dives $year^{-1}$ (mean ± SE; Fig. S1). The data show an increase in the number of SCUBA dives during the first ten years following the establishment of the MPA, reaching a peak of 5728 dives in 2013. However, from 2018 to 2023, the number of SCUBA dives has fluctuated significantly, dropping to a minimum of 2140 in 2020, a year heavily impacted by the COVID-19 pandemic.

Frequentation is not evenly distributed throughout the year but rather peaks during the summer months of July, August, and September. The use of dive sites is unbalanced, with two (1 and 7) of the six sites designated for touristic diving activities accounting for over 65 % of the total dives in 2022 and 2023 (Fig. S2).

3.2. SCUBA divers' behaviour and diver-substrate interaction hotspots

A total of 87 SCUBA divers were observed: male accounted for the 87 % of the SCUBA divers visiting the MPA. The experience *per* SCUBA diver varied greatly between 7 and 8000 dives completed during the lifetime. As for certification level, 62 % of the monitored tourists were Advanced Open Water, 22 % were Dive Master or instructor, and 16 % were Rescue divers. A substantial portion of the monitored SCUBA divers (50 %) were equipped with camera.

The 92 % of the monitored SCUBA divers were recorded interacting with the substrate, for a total of 436 diver-substrate interactions (5.0 ± 0.5 interactions dive^{-1}, 0.13 ± 0.01 interaction min^{-1}); however, only 1 % of these interactions were recorded as physical damage to benthic organisms.

The observers did not affect the conduct of divers as highlighted by the number of interactions with the substrate which did not vary significantly between the two observations of the same SCUBA divers (Wilcoxon-Mann-Whitney test, $W = 3$, p-value = 0.371), who were conscious of being observed during the second sampling dive.

Fig. 2a presents the results of the MCA in a two-dimensional plot, with the first two dimensions explaining 44.5 % of the total variance. The position of the variables relative to the axes indicates their contribution to defining the two dimensions. The results show that the number of interactions is strongly positively correlated with the first dimension, which is mainly explained by the variables experience and camera. On the other hand, gender and certification had a low contribution to the first dimension. To clarify the contribution of experience and camera to the first dimension, we estimated the confidence ellipses (95 %) based on the levels of these variables (Fig. 2b, c). Both the ellipse enclosing observations with experience >500 and the ellipse associated with the use of the camera are positioned along the x-axis, in the second and third quadrants of the plane. This dimension is highly correlated with the number of diver-substrate interactions. Moreover, these ellipses show a very similar area and are partially overlapping. As a result, the dependence between camera and experience was highlighted by the Chi-squared test ($\chi^2 = 13.918$, p-value = 0.003).

No significant differences were found in the number of diver-substrate interactions between the two genders (Wilcoxon-Mann-Whitney test, $W = 476.5$, p-value = 0.555) and among diving certifications (Kruskal-Wallis test, $\chi^2 = 1.450$, p-value = 0.484; Table S2). As for the use of camera, photographers interact with the substrate significantly more frequently than non-photographers (Wilcoxon-Mann-Whitney test, $W = 460$, p-value <0.001). Diver-substrate interactions were significantly affected by level of diving experience (Kruskal-Wallis test, $\chi^2 = 13.801$, p-value = 0.003; Table S2). In particular, the highest number of interactions was recorded among SCUBA divers with higher diving experience (100–500 and > 500 dives), who differed significantly from SCUBA divers with 0–50 dives (Dunn's test, p-value = 0.016 and p-value = 0.020, respectively).

Dive phase had a significant effect on the number of diver-substrate interactions, as indicated by the Kruskal–Wallis test ($\chi^2 = 14.669$, p-value <0.001; Fig. 3). Most interactions occurred during the middle phase, which differed significantly from the initial (p-value <0.001) and final (p-value = 0.020) phases, as shown by the Dunn's test.

Diver-substrate interactions occurred principally through their fins (49 % of the recorded interactions), knees (16 %), and scuba gear (0.2 %): these can be categorized as unintentional interactions since it is

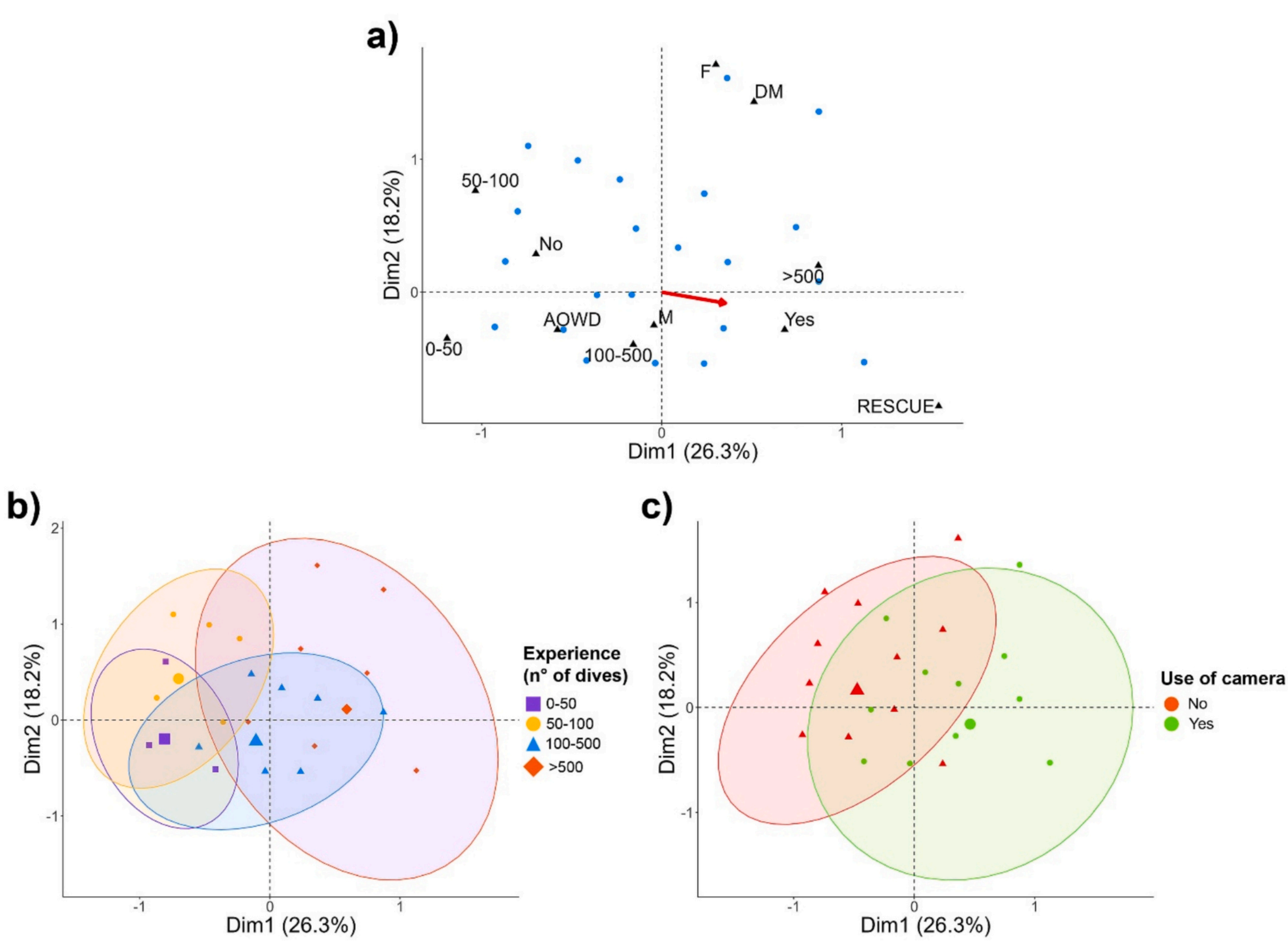

Fig. 2. The x- and y-axes represent the first and second dimensions (Dim1 and Dim2) of the MCA (a). The red arrow indicates the quantitative variable, i.e. the number of diver-substrate interactions; in black, the levels of qualitative variables are illustrated: gender (M, male, and F, Female), certification (AOWD, Advanced Open Water; RESCUE, Rescue Diver; and DM, Dive Master), experience (0–50; 50–100; 100–500; and > 500 dives) and camera (Yes and No); the blue points represent the observations. The 95 % confidence ellipses highlight observations as a function of levels of the variables experience (b) and use of camera (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

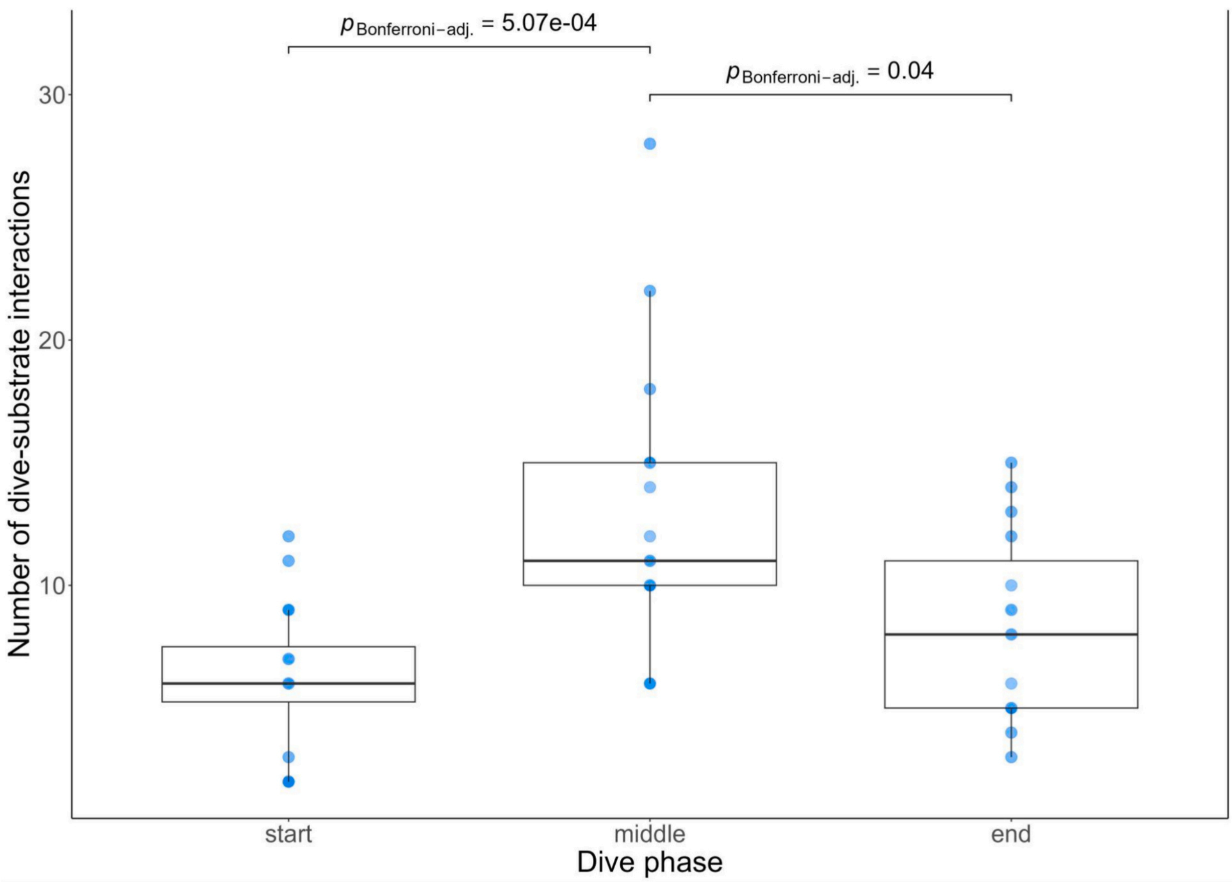

Fig. 3. Distribution of the number of diver-substrate interactions in relation to dive phases (start, middle, and end); individual observations are shown as blue points. The box corresponding to the middle phase shows higher values of diver-substrate interaction and appears visually distinct from boxes corresponding to the start and end phases. Statistical differences were determined using Kruskal-Wallis test, followed by Dunn's test. Square brackets highlight the significant differences among dive phases, along with the corresponding adjusted *p*-value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presumed the divers lacked direct visual or sensory awareness of the seabed. In contrast, interactions interpreted as intentional, resulting from placing hands or a camera directly on the seabed in front, accounted for 30 % and 4 %, respectively. Differences in percentages among categories related to body part or equipment contacting the seabed were deemed significant by the multinomial test (*p*-value $<$0.001).

The same number of interactions by SCUBA divers affected both the organisms structuring to the erect layer (50 %) and those belonging to the basal and intermediate layer (50 %).

The areas identified as diver-substrate interaction hotspots through KDE were located near the most frequently used dive sites (i.e., 1 and 7) by diving centres in 2022 and 2023 (Fig. 4). Specifically, points with moderate or high levels of interaction were concentrated both in morphologically heterogeneous and gently sloping seabeds. Near buoy 1, interactions affected the top of the shoal, between 18 and 21 m of depth, and along its northeastern edge, where a 2-m-high rock edge with numerous cavities shaped the seabed morphology between 21 and 24 m of depth. At dive site 7, interactions were concentrated around the mooring buoy, where the seabed is characterized by rocky outcrops, crevices, and pronounced vertical walls developing between 24 and 30 m depth. Buoys 2, 3, and 6 were evidently less affected by interactions, likely due to low levels of use.

3.3. Benthic communities structure

Mean relative frequencies of 12 monitored taxa were reported in Supplementary Material (Fig. S3). Stations in the deep layer showed greater variability compared to the shallower ones. In both depth layers, none of the monitored organisms exhibited a clear decrease between the periods before and after the peak of the diving season. However, in the deep layer, a reduction was observed for *A. calveti*, *S. cervicornis*, *M. truncata*, *L. pruvoti*, and *P. clavata*, likely due to the seasonal development of erect brown algae (i.e., *Arthrocladia villosa* (Hudson) Duby, 1830 and *Sporochnus pedunculatus* (Hudson) C. Agardh, 1817), which led to an underestimation of their relative frequencies. On the other hand, in the shallow layer, the same aforementioned species showed a positive variation, probably due to the presence of benthic mucilaginous aggregates at the beginning of summer, resulting in an underestimation before the peak of the diving season. The species *C. caespitosa* and *E. singularis* were excluded from the following analysis due to extremely low frequencies of observations, whereas *A. calveti* and *S. cervicornis* were grouped due to similarities in their colony morphology.

The PCoA ordination plot (60.5 % of total variance explained by the first two axes) showed the degree of similarity among observations based on frequency data of the monitored taxa (Fig. 5): the confidence ellipses defined according to condition overlapped (Fig. 5a), with scattered observations before and after the peak of the diving season. Conversely, the separation among depth layers was appreciable (Fig. 5b): in this regard, deep observations displayed greater dispersion, indicating higher variability if compared to shallower ones.

In Fig. 6 we report the α-diversity for a range of values of the generalized biodiversity index of order *q* for the two depth layers. As for condition, in the shallow layer, α-diversity seemed very similar both in

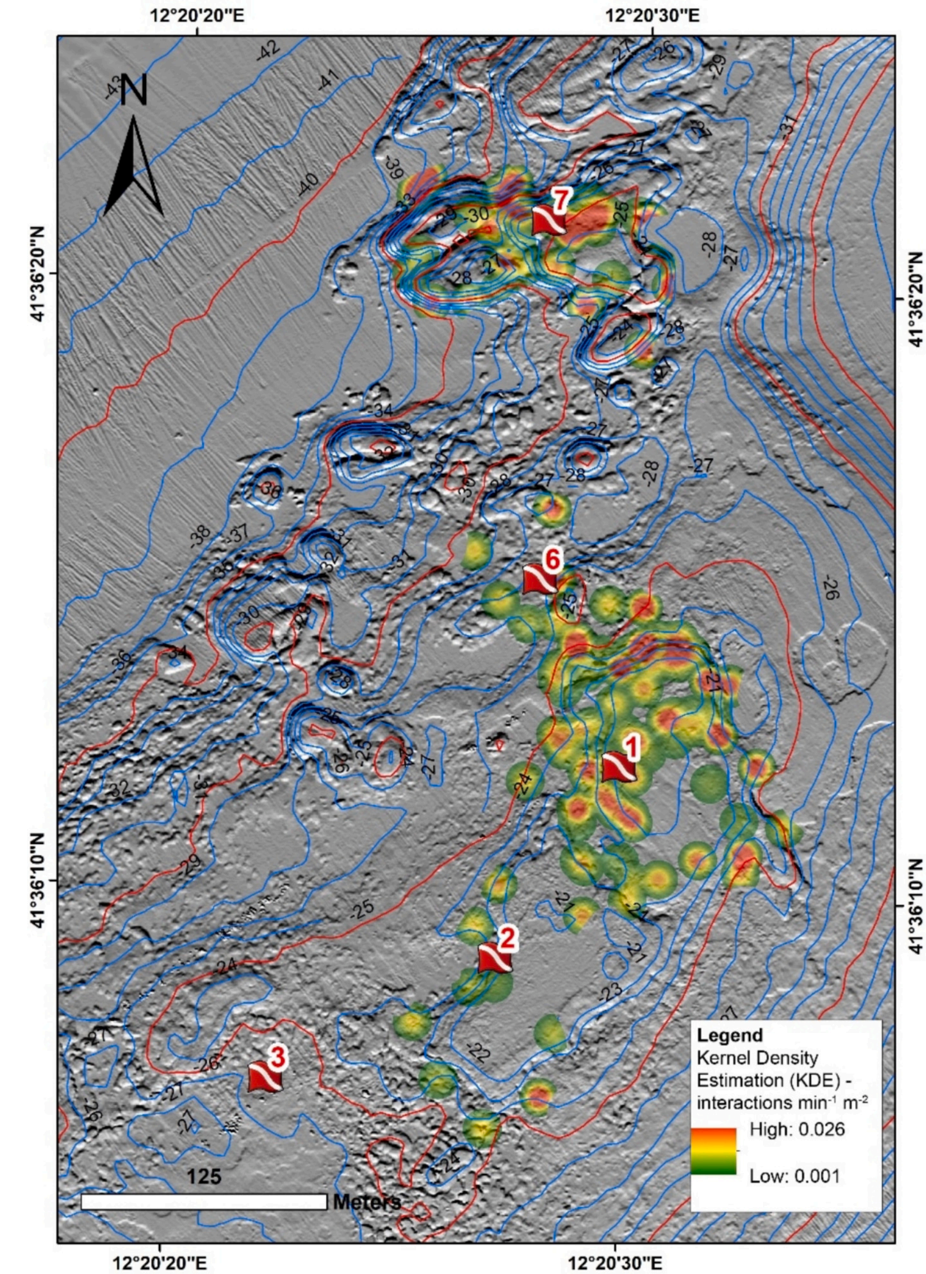

Fig. 4. Kernel Density Estimation map showing the diver-substrate interaction hotspots in the MPA Secche di Tor Paterno. The green areas represent low (0.001 interactions min^{-1} m^{-2}) while the red areas indicate high interactions (0.026 interactions min^{-1} m^{-2}). The areas with no interactions are transparent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

terms of condition and time of sampling, for all values of q (Fig. 6a). In the deep layer, α-diversity indices after the peak of the diving season seemed less diverse than before (Fig. 6a). However, their confidence bands partially overlapped.

To assess the significant variations in α-diversity indices in relation to condition, dive site, and time of sampling, we estimated three models (Table S3). The explanatory variables (condition, dive site, and time of sampling) were treated as interacting factors. For all models, the intercept—defined by frequented condition, deep layer, and after the peak of the diving season — was deemed significant. In all models, no significant differences were observed between condition at the same depth. The α-diversity expressed as the number of species ($q = 0$) showed no significant differences for all interactions of variables' levels. As for $q = 1$ (α-diversity expressed as the Shannon Index), significant variations were observed according to time of sampling (p-value = 0.007), depth (p-value = 0.027), and the combined effect of condition, depth, and time of sampling (p-value = 0026; Table S3). Time of sampling (p-value = 0.005), and the interaction between depth and time of sampling (p-value = 0.030) revealed significant effects on α-diversity at $q = 2$ (**Table S3**). These results suggest that time of sampling and depth, as well as their interactions, had the strongest influence on α-diversity patterns. In contrast, the condition did not show direct significant effects on α-diversity patterns. This may indicate that the structure of benthic communities within the MPA is more strongly influenced by environmental variations (such as season and depth) than by the pressure of SCUBA diving activities.

4. Discussion

The approach applied in this study delineates a comprehensive

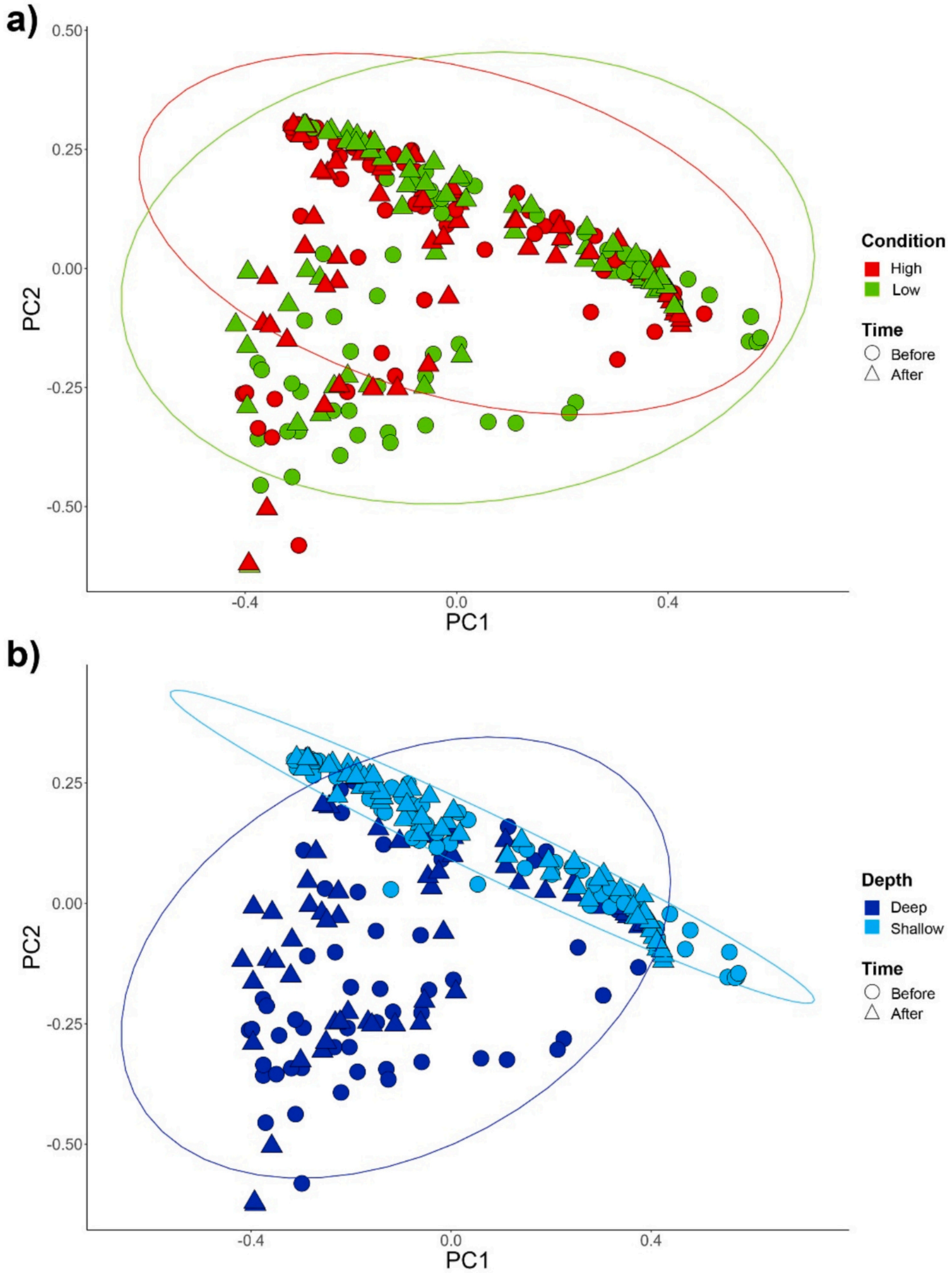

Fig. 5. PCoA plots with the 95 % confidence ellipses highlighting observations as a function of levels of the variables condition (frequented in red, unfrequented in green; panel a) and depth layer (deep in dark blue, shallow in light blue; panel b). In both plots, the variable time of sampling is represented by the shape of points, with triangles indicating before and circles indicating after the peak of the diving season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

framework for assessing the potential impacts of SCUBA diving activities at Secche di Tor Paterno MPA of Rome. The total number of SCUBA dives *per* year was lower if compared to other Mediterranean MPAs, such as the Portofino MPA, with 40,000 annual dives (Betti et al., 2019), or Sierra Helada Marine Park, which hosts over 20,000 divers annually (Luna et al., 2009). The distance from the coast, combined with the absence of natural shelters that hinder accessibility during adverse weather and sea conditions, along with local hydrodynamic patterns that reduce visibility due to sediment input from the Tiber River, significantly influences visitation rates to the MPA. These factors contribute to the inter- and intra-annual variations (Pitarch et al., 2019; Varghese et al., 2024). The summer months recorded the highest number of SCUBA dives due to more favourable weather, improved underwater visibility, and greater leisure time availability for tourists. The non-uniform use of sites was attributed to the presence of areas with high aesthetic-naturalistic value, which particularly attract SCUBA divers, resulting in greater exposure to the disturbance caused by diving activities.

The rate of interaction recorded in the present study (0.13 interaction min^{-1}) was considerably lower if compared to those reported by other authors: 0.36 interaction min^{-1} at Capo Gallo (Isola delle Femmine; Di Franco et al., 2009), 0.59 interaction min^{-1} at Ponta do Ouro (Mozambique; Lucrezi et al., 2021), and 4.12 interaction min^{-1} in the Sierra Helada Marine Park (Spain, Luna et al., 2009). The differences observed can be attributed to management policies, especially those at the micro-level (Giglio et al., 2020), such as the pre-dive briefing, maximum SCUBA divers *per* site, and restricted access of Open Water-certified divers. This effectively excludes a large portion of the diving

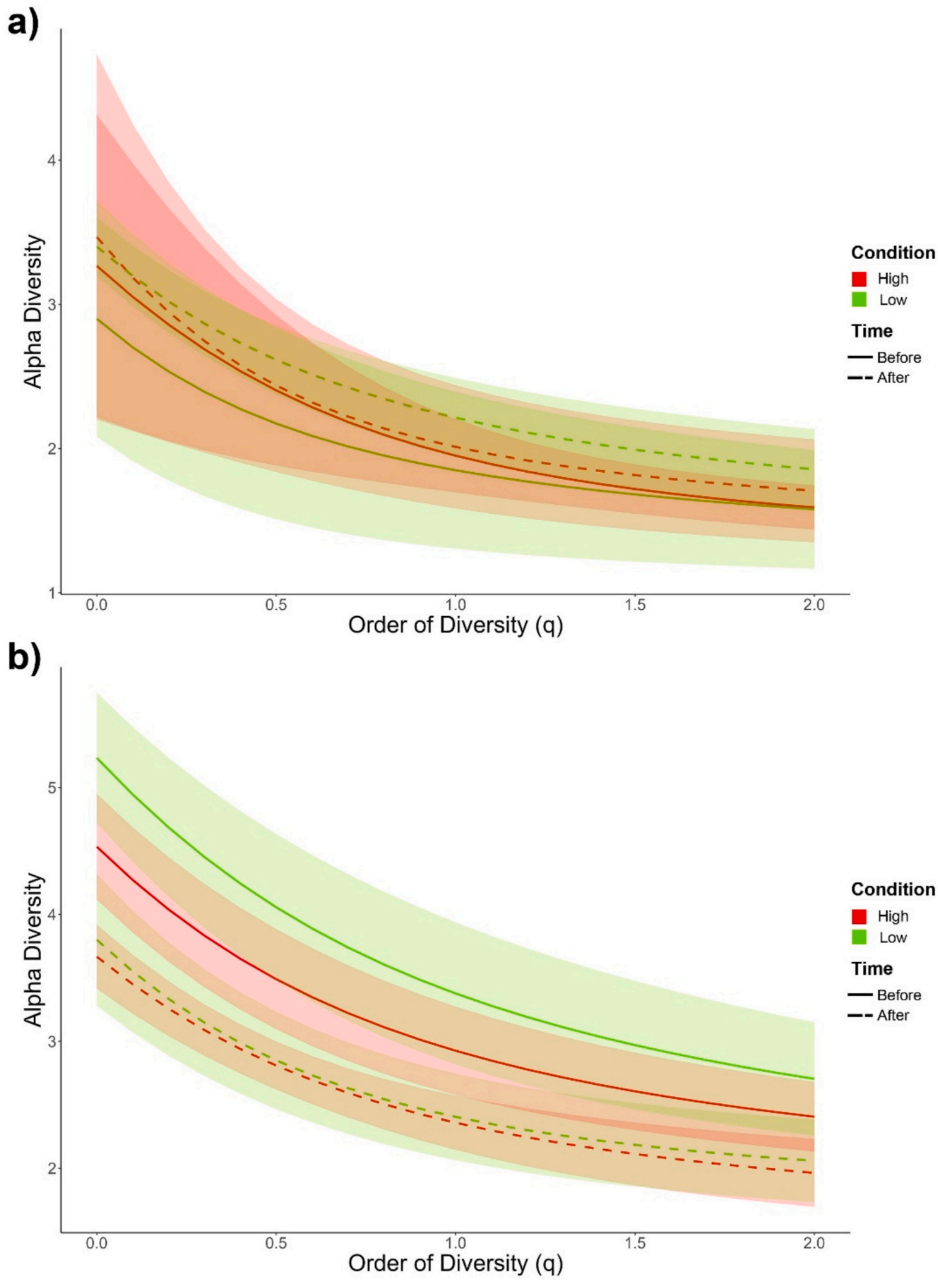

Fig. 6. The α-diversity indices for different q and their 95 % confidence bands distinguished among condition (frequented in red, unfrequented in green) and time of sampling (before as solid line, after as dashed line), in shallow (a) and deep (b) depth layers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

community who usually visit MPAs. Specifically, SCUBA divers with entry-level diving certification (i.e., Open Water divers) frequently struggle to maintain proper buoyancy control or may lack adequate training, which increases the risk of physical interaction with the reef ecosystem (Hammerton, 2016; Toyoshima and Nadaoka, 2015). Therefore, the exclusion of this SCUBA diver category in the Secche di Tor Paterno MPA likely plays a key role in maintaining lower interaction rates compared to other MPAs where such restrictions are not enforced.

Most SCUBA divers visiting the Secche di Tor Paterno MPA were male. While some authors highlighted that women may exhibit more respectful and technically proficient behaviour underwater (Jiménez-Gutiérrez et al., 2009), the present study found no significant gender differences in diver-substrate interactions, also considering the asymmetrical distribution of the sampled population by gender. However, it is difficult to disentangle gender differences from other underlying factors, such as individual experience, training level, or the diver attitude towards environmental conservation.

As observed in previous studies (Di Franco et al., 2009; McBride, 2021), no significant effect of dive certification on interaction rates was depicted, as it does not necessarily correspond to improved diving practices. Open Water divers often have the highest interaction rates (Giglio et al., 2020, 2022), but they were not included in this study due to MPA regulations.

On the contrary, the use of camera significantly increased the number of diver-substrate interactions. Photographers often stabilize themselves by holding onto reef surfaces and inadvertently interact with the reef while attempting to take pictures (Giglio et al., 2016, 2020; Hammerton, 2018).

Another variable that significantly affected the number of diver-substrate interactions was diving experience. Most interactions were recorded among more experienced SCUBA divers. Although greater diving experience might suggest improved diving skills, such as buoyancy and swimming control (Davis and Tisdell, 1995; Giglio et al., 2016), several studies have observed a higher number of interactions among experienced divers, consistent with our results (Di Franco et al., 2009; Hammerton, 2017; Lucrezi et al., 2021). Experienced SCUBA divers often feel more confident approaching the substrate and interacting with organisms, while less experienced SCUBA divers may adopt more cautious practices (Hammerton, 2017). Moreover, this study highlights that the diving experience and the use of photographic equipment are interdependent factors: more experienced SCUBA divers were also more likely to use underwater cameras. The findings further highlight the challenges in examining a single factor without considering the broader range of variables, and their dependence, that shape SCUBA divers' behaviour.

Most diver-substrate interactions were recorded during the middle phase of the dives. During this phase, areas with high aesthetic-naturalistic value were observed. These features attract experienced SCUBA divers and underwater photographers, encouraging them to approach the substrate to capture pictures. Previous studies have identified the beginning of the dive as a more critical phase, as SCUBA divers adjust their buoyancy and coordinate buddy-diving procedures (Di Franco et al., 2009; Camp and Fraser, 2012; Giglio et al., 2022). However, the SCUBA divers primarily responsible for such disturbances are typically Open Water divers, i.e. the group of users whose access is restricted at Secche di Tor Paterno MPA.

SCUBA divers impact the reef mostly through fins, as they often use them for propulsion and allow them to hang lower than the rest of their body. On the contrary, hands are often used intentionally to preserve neutral buoyancy during visual observation and photographic documentation (Balzaretti-Merino et al., 2021; Lucrezi et al., 2021; Giglio et al., 2022). Our results indicate that interactions through fins occurred more frequently than those made by hands, suggesting voluntary interactions were relatively less common compared to involuntary interactions. This may be a result of the pre-dive briefing implemented by the management authority. Indeed, as observed in previous studies (Webler and Jakubowski, 2016; Giglio et al., 2018), educational briefings that focus on the potential impact on benthic communities help raise SCUBA diver awareness and promote the adoption of low-impact behaviours, significantly reducing voluntary interaction rates with benthic reef organisms.

The above-described interactions affected to a similar degree both the basal-intermediate and erect layers of the community, suggesting that the responses of organisms belonging to these two layers are likely to be consistent.

The analysis of the distribution of interactions on the seafloor provides a spatially explicit tool that enables further implementation of micro-level strategies, such as pre-dive briefings, in-water interventions by guides, zoning of diving activities within the MPA, and the sampling designs adopted for monitoring (Giglio et al., 2020). Such insights allow management measures to be tailored to the specific features of the site, promoting lower-impact behaviours in proximity to certain areas or during specific phases of the dive. However, it is important to underline that this tool is subject to accuracy bias, as it is based on the integration of *in-situ* observations, timing of the interaction, and *a posteriori* reconstruction of the diving route. The inability to accurately georeferencing each interaction (e.g., using Ultra-Short Base Line tracking system) represents the primary limitation of this analysis. Nevertheless, the spatial analysis is consistent with the other results: the heatmap highlights seabed areas, at most frequented dive sites, that are aesthetically and naturally interesting for SCUBA divers and underwater photographers. This opens further perspective about the significant implications of aesthetic and cultural value for biodiversity conservation and underscores the importance of considering these factors in the effective management of touristic activities within MPAs (Waechter et al., 2023).

The analysis of the frequencies of the 12 bioindicator species and the use of synthetic biodiversity metrics showed how the structure of coralligenous communities did not change significantly according to frequentation and peak of SCUBA dives, suggesting a sustainability of the touristic activities within the MPA. Although the studied species provide only a partial representation of the community, they serve as optimal proxies, due to their aesthetic appeal for SCUBA divers, leading to close approaches that increase the likelihood of impact, the role in the functioning of benthic ecosystems (Gili and Coma, 1998), and fragile skeletal components and erect or massive growth forms render them highly susceptible to interactions (Betti et al., 2023). In particular, α-diversity, at different values of q, well summarized the effects of touristic activities at community level, indicating that the carrying capacity of the MPA has not been exceeded. This capacity is defined as the number of SCUBA divers a site can accommodate without experiencing degradation or alterations in the structure of its communities (Davis and Tisdell, 1995). The small differences observed before and after the peak visitation period are depth-related and could be attributed to the small-scale heterogeneity of coralligenous assemblages (Piazzi et al., 2021) and the seasonal colonization dynamics of algal taxa. The former may be exacerbated by the challenges of replicating photographic sampling methods on the same surfaces, while the latter is particularly influenced by seasonal benthic mucilaginous aggregates (Piazzi et al., 2018).

5. Conclusions

The anthropic activities permitted within MPAs can impact marine communities, necessitating continuous monitoring to ensure the effectiveness of management measures. This is particularly relevant when considering the broader context, which also includes the effects of climate change. The cumulative impact of both stressors risks undermining the conservation efforts carried out by MPAs, potentially compromising their ability to protect marine ecosystems (Bates et al., 2019; Zentner et al., 2023). The present study provides a new approach to assess the impact of diving activities within an MPA, which considers three different levels of analysis: use-quantification, identification and localization of disturbance, and evaluation of its effects on benthic communities. In this way, we obtained a comprehensive view of the impact of diving activities in the Secche di Tor Paterno MPA of Rome, providing valuable insights into current pressures and communities' responses. This multi-faceted approach, and resulting comprehensive understanding of the impact of diving activities in the MPA, serve as a foundation for improving management interventions and conservation strategies within an adaptive management framework. Moreover, the results of this study offer a valuable baseline for future assessment of benthic communities and their responses within the MPA to both anthropic and environmental pressures. Indeed, effective management, characterized by frequent and detailed assessments of ecosystem health status in protected areas, can help reduce the synergistic pressures affecting marine communities and mitigate or delay the impacts of climate change, thereby maximizing the effectiveness of MPAs.

CRediT authorship contribution statement

Letizia Ottone: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Gianluca Mancini:** Investigation, Formal analysis, Data curation. **Daniele Ventura:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Andrea Belluscio:** Writing – review & editing, Data curation. **Giovanna Jona Lasinio:** Writing – review & editing, Formal analysis, Data curation. **Edoardo Casoli:** Writing – original draft, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

Acknowledgment

This research was supported by the Managing Authority of the Marine Protected Area Secche di Tor Paterno, RomaNatura, through the project “Assessment and monitoring of underwater resources for the sustainable development of scuba diving tourism in the MPA Secche di Tor Paterno”, awarded to the Department of Environmental Biology, Sapienza University of Rome. The authors gratefully acknowledge Giacomo Cardinali, Ludovica Trolese, and Sabrina Marchionni (Blue Marlin Diving Center) for their valuable assistance during field data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118504.

Data availability

Data will be made available on request.

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