Marine Pollution Bulletin 216 (2025) 118004

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Assessing the hidden threat of removing abandoned fishing gear from coralligenous habitats: a new monitoring protocol

Annalisa Azzola[a,b,1,*], Francesco Pelizza[a,1], Fabrizio Atzori[c], Viola Maria Atzeni[c], Nicoletta Cadoni[c], Lara Carosso[c], Maria Leonor Garcia Gutiérrez[c], Ilaria Mancini[a], Chiara Paoli[a,b], Luigi Piazzi[d], Monica Montefalcone[a,b]

[a] *Department of Earth, Environment and Life Sciences (DiSTAV), University of Genova, Italy*
[b] *NBFC, National Biodiversity Future Center, Palermo, Italy*
[c] *Capo Carbonara Marine Protected Area, Cagliari, Italy*
[d] *Centro Interuniversitario di Biologia Marina ed Ecologia Applicata 'G. Bacci', viale N. Sauro 4, 57128 Livorno, Italy*

A R T I C L E I N F O

Keywords:
ALDFG
Coralligenous reef
Ecological indices
Capo carbonara MPA
Mediterranean Sea

A B S T R A C T

Fishing gear poses a serious threat to coralligenous habitat, causing several damages both during fishing activities and when lost on the seafloor. Further impacts can arise during the removal of abandoned, lost or otherwise discarded fishing gear (ALDFG). The slow growth rate of the coralligenous species suggests a reduced ability of this habitat to recover after an extensive damage. This work proposes a protocol to assess the impact of ALDFG removal on coralligenous habitat. Seven coralligenous reefs in the Capo Carbonara Marine Protected Area affected by ALDFG were compared with nearby unaffected reefs in three time-periods (before the ALDFG removal, immediately after, and one year later), applying the BACI (Before-After/Control-Impact) design. Data collection followed the STAR protocol (STAndaRdized coralligenous evaluation procedure) to apply the COARSE index (Coralligenous Assessment by Reef Scape Estimate) for the assessment of the ecological status of these habitats. Results showed a decline in ecological status only at two impact stations immediately after the ALDFG removal, followed by a recovery one year later. The intermediate layer of the coralligenous reefs was the most affected due to the loss of fast-growing species that colonized the ALDFG and were removed with them. The proposed protocol proved effective in assessing the impact of ALDFG removal on coralligenous habitat. Considering the importance of maintaining the seascape integrity, which includes the cleaning of ALDFG, this study highlights how the ALDFG removal is recommended only after careful evaluation and carried out in a manner that does not create further damage to sessile communities.

1. Introduction

Approximately 10 % of marine debris worldwide is attributed to discarded fishing gear, which includes used nets, longlines, and cages that are either lost or abandoned (Macfadyen et al., 2009). In the Mediterranean Sea, the amount of abandoned, lost or otherwise discarded fishing gear (ALDFG) is estimated at around 2637–3342 t annually (Golik, 1997). Since fishing gear is designed to catch marine organisms, ALDFG has a greater impact on marine life than any other marine debris (Consoli et al., 2019; Richardson et al., 2022). Any type of gear lost on the seafloor during fishing activities can continue to operate, capturing or harming marine species while also scraping the substrate (Stevens, 2020). This can result in additional negative effects on the entire ecosystem, including a loss of biodiversity (Appolloni et al., 2017), alterations in community composition (Sheehan et al., 2017), and the degradation of nursery areas (Melli et al., 2014). Considering the threat posed by derelict fishing gear to the conservation of the Mediterranean biodiversity, the European Union has introduced laws, measures, and monitoring programmes, such as the Marine Strategy Framework Directive (MSFD; European Commission, 2008) and the Nature Restoration Law (NRL; European Parliament, 2024), to detect, protect, and restore vulnerable habitats that are sensitive to ALDFG.

Coralligenous reefs are among the most impacted habitats by ALDFG (Ferrigno et al., 2017; Enrichetti et al., 2019a; Ruitton et al., 2019;

* Corresponding author at: Department of Earth, Environment and Life Sciences (DiSTAV), University of Genova, Italy.
E-mail address: annalisa.azzola@gmail.com (A. Azzola).
[1] These authors are first co-authors

https://doi.org/10.1016/j.marpolbul.2025.118004
Received 21 February 2025; Received in revised form 14 April 2025; Accepted 15 April 2025

Gimenez et al., 2022). Although it covers only 0.1 % of the total area of the Mediterranean basin, coralligenous habitat hosts 20 % of the Mediterranean species (Martin et al., 2014), representing one of the most important marine habitats globally due to its extensive coverage, rich biodiversity, and high productivity (Ballesteros, 2006). Coralligenous habitat occurs typically at depths starting from 30 to 40 m and extends to the limit of the photic zone, even up to 200 m (Ferrigno et al., 2018a). Due to the wide bathymetric distribution and the presence of commercially important species, coralligenous habitat is particularly exposed to local fishing activities and the subsequent ALDFG impact compared to other Mediterranean ecosystems (Bo et al., 2014; Enrichetti et al., 2019a; Ferrigno et al., 2021). Moreover, nets and longlines often get entangled in the complex three-dimensional structure that characterizes these habitats, causing breakage and necrosis in many erect species, other than capturing vagile organisms and suffocating sessile algae and animals (Bo et al., 2014). These effects often result in a decrease in habitat heterogeneity, structural integrity, biodiversity, and ecosystem function (Bavestrello et al., 1997; Ballesteros, 2006; Martin et al., 2014; Enrichetti et al., 2019a; Do and Armstrong, 2023).

Coralligenous habitat is structured into three distinct layers (basal, intermediate, and upper) with unique ecological characteristics, and responding differently to the presence of ALDFG. The basal layer, primarily composed of encrusting organisms that grow to heights of less than 1 cm (Gatti et al., 2012), provides essential foundational support and is susceptible to physical obstruction and abrasion (Saldanha et al., 2003; Clark and Koslow, 2007). The intermediate and upper layers are generally characterized by vertically growing organisms, which reach heights of 1–10 cm in the first layer and more than 10 cm in the second one (Gatti et al., 2012, 2015). These canopy-forming species are particularly vulnerable to entanglement or physical damage (Ferrigno et al., 2021; Macfadyen et al., 2009), and their necrotic tissue can become overgrown by epibionts, further altering the habitat structure (Ferrigno et al., 2021; Macfadyen et al., 2009).

Numerous quantitative studies have been conducted to understand the impact of ALDFG on soft and hard bottom communities (Williams et al., 2010; Bo et al., 2014; Ruitton et al., 2019; Angiolillo and Fortibuoni, 2020; Enrichetti et al., 2021; Ferrigno et al., 2021). However, little is still known on the recovery capacity of coralligenous habitat in response to impact from fishing gears (Auster and Langton, 1999; Ferrigno et al., 2018a). The slow growth rates of the most abundant and structurally important species within the coralligenous habitat indicate a limited capacity for recovery after extensive mechanical damage (Piazzi et al., 2012). This slow regeneration means that once impacted, this habitat may take years, or even decades, to return to its original state (Pinna et al., 2024). Evidence has shown that the presence of ALDFG on coralligenous habitat contributes to significant biodiversity loss (Ferrigno et al., 2021). Additionally, the removal of ALDFG may cause further damage, particularly if it takes place long after their abandonment on the seafloor, as all the species that have colonized the debris are inevitably removed along with it (Ruitton et al., 2020). While some knowledge is available, a comprehensive understanding of the impact of ALDFG on coralligenous habitat, especially concerning the consequences of its removal from the seafloor, remains limited. Meaningful insights into the resilience of coralligenous habitat to this type of disturbance requires long-term monitoring efforts conducted after the removal of ALDFG. Such studies are essential to assess recovery dynamics, identify potential thresholds of resilience, and guide the development of effective management and restoration strategies.

This study presents a new protocol aimed at enhancing our understanding of the impact of ALDFG on the ecological status of coralligenous habitat. It also provides a framework for evaluating the effects of ALDFG removal and assessing the subsequent recovery capacity of this ecosystem. The ecological status of coralligenous reefs in the Capo Carbonara Marine Protected Area (SE Sardinia, Italy) affected by ALDFG was assessed using the BACI sampling design (Before-After/Control-Impact; Underwood, 1992, 1997). Evaluations were conducted before, immediately after, and one year following the ALDFG removal, with results compared to nearby control sites where no ALDFG was present. Data collection followed the STAR protocol (STAndaRdized coralligenous evaluation procedure; Piazzi et al., 2019; Piazzi et al., 2025) for a standardized monitoring on coralligenous habitat. The ecological status of the coralligenous reefs was measured with the COARSE index (Coralligenous Assessment by Reef Scape Estimate; Gatti et al., 2012, 2015), as it allows for separate analysis on the three distinct layers of the coralligenous habitat, each responding differently to the impact of ALDFG.

2. Methods

2.1. Study area

The Capo Carbonara Marine Protected Area (MPA) is located near the town of Villasimius in south-eastern Sardinia (Italy) and was established by the Italian Ministry of the Environment in 1998. The MPA covers an area of 14,360 ha and includes the Cavoli Island, the Serpentara Island and numerous smaller islets and shoals. The MPA is divided into four different zones (Fig. 1): i) zone A, which is the integral reserve; ii) zone B, which is the general reserve; iii) zone C, which is the partial reserve; and iv) zone D, which is the experimental reserve. Fishing activities are forbidden in zone A, while in zones B, C, and D they are permitted exclusively for residents of Villasimius.

Around the islands and along the coast, rocky reefs of the deeper infralittoral and the circalittoral zones are characterized by coralligenous habitat that hosts assemblages dominated by calcareous algae, gorgonians, and sponges (Orrù et al., 2005; Azzola et al., 2023). The seafloor of the Capo Carbonara MPA is characterized by granitic rocks that create numerous pinnacles and shoals, which promote the entanglement and accumulation of lost fishing gear and other anthropogenic debris (Moschino et al., 2019).

2.2. Field activities

Surveying activities were carried out at seven sites within the zones B and C of the MPA (Fig. 1), where the presence of ALDFG was reported (Fig. 2): Capo Boi (9.44066°E, 39.11313°N), Dotti (39.0764°N; 9.53995°E), Gorgonie (39.08426°N; 9.49423°E), Punta Karalis (9.607633°E, 39.136667°N), Punta la Guardia (9.606083°E, 39.133800°N), Santa Caterina (9.49272°E, 39.08910°N), and Secca di Mezzo (9.52820°E, 39.05938°N).

According to the BACI sampling design (Before-After/Control-Impact), each site was surveyed at three distinct time periods: before the removal of ALDFG (B), immediately after (A), and one year later (O). The sites Capo Boi, Punta Karalis, Punta la Guardia, Santa Caterina and Secca di Mezzo were firstly surveyed in July 2022, then in September 2022, and in September 2023. The sites Dotti and Gorgonie were surveyed in July 2023, then in September 2023, and in September 2024. At each site, two stations were designated: the impact station (I), where ALDFG was present, and the control station (C), which did not have any ALDFG and was located nearby, sharing the same environmental characteristics. A total of 14 stations were investigated.

Data collection followed the STAR protocol (Piazzi et al., 2019; Piazzi et al., 2025) and the ecological quality was evaluated through the COARSE index (Gatti et al., 2012, 2015). At each station, three replicated visual assessments were conducted, each covering an area of 1.5 m^2, at depths ranging from 30 to 40 m. During each replicate, various descriptors were recorded for each of the three layers that compose the coralligenous habitat. In the basal layer, the percent cover of four benthic categories was visually estimated: i) encrusting calcified Rhodophyta (ECR), ii) non-calcified encrusting algae (NCEA), iii) encrusting animals (EA), and iv) turf-forming algae and sediment (TURF/SED). In addition, a semi-quantitative assessment of the borer species marks (e.g., clionid papillae and bivalve holes) was performed by attributing three

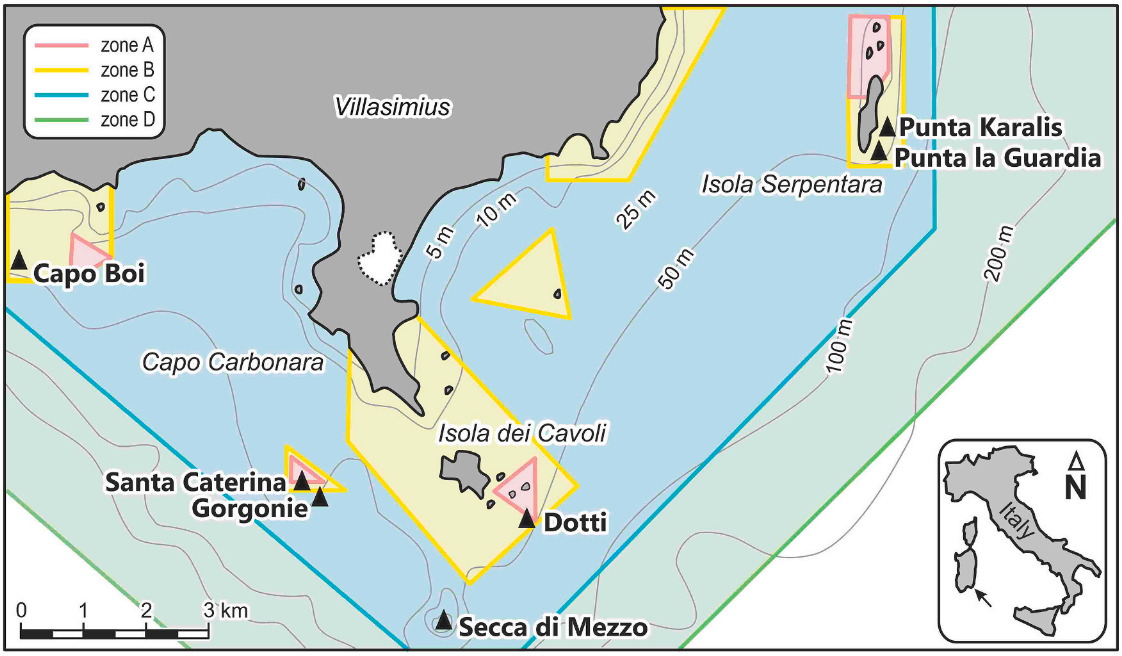

Fig. 1. Map of Capo Carbonara MPA with the zones at different levels of protection and the seven sites (black triangle) where monitoring activities for the evaluation of abandoned, lost or otherwise discarded fishing gears (ALDFG) impact were conducted.

Fig. 2. Examples of abandoned, lost or otherwise discarded fishing gear (ALDFG) on the Capo Carbonara MPA sea bottoms (Photos by Egidio Trainito).

classes of abundance (common, occasional, absent). Lastly, the thickness of the calcareous concretion was measured in millimetres using a handheld penetrometer. In the intermediate layer, a list of conspicuous species was compiled. In the upper layer, visual estimates were made for the percent cover of each erect species and the percent cover of necrosis within each population, and the maximum height of the tallest specimen was measured with a ruler (Gatti et al., 2012, 2015).

The removal of ALDFG at each impact stations was carried out by the MPA staff under the supervision of biologists to minimise the damages on coralligenous assemblages during the removal operations. Once the gear was retrieved from the water, its length and total surface area were measured. A list of visually identifiable species that were either entangled in or encrusted on the gear was compiled, and a semi-quantitative assessment of their abundance (expressed as percent cover) was performed.

2.3. Data analysis

2.3.1. Ecological status of coralligenous reefs

The COARSE index (Gatti et al., 2012, 2015) was applied to define the ecological status of coralligenous reefs at both the impact and the control stations across the three time periods, allowing for the identification of any change before, immediately after, and one year following the ALDFG removal. The ecological status of each individual coralligenous layer (basal, intermediate, and upper) was also assessed at each station to identify the most affected layer by the ALDFG.

A total of nine descriptors were considered for the three layers (Gatti et al., 2015). For the basal layer: (i) cover of ECR, NCEA, EA, TURF/SED, (ii) thickness and consistency of calcareous layer, and (iii) borers marks. For the intermediate layer: (iv) species richness (SR), (v) erect calcified organisms (ECO), and (vi) sensitivity of bryozoans. For the upper layer: (vii) total cover of erect species, viii) maximum height (MH) of each species, and (ix) percentage of necrosis for each species. The criteria adopted to assign scores to each descriptor, for each replicate, are summarized in the Table S1. Likewise, the classification to define the ecological status of coralligenous habitat is showed in the Table S2.

To analyse temporal changes in the basal and intermediate layers descriptors, used to compute the COARSE index, two-way analyses of variance (ANOVAs) were performed with two fixed and orthogonal factors: 'station type' (control vs. impact) and 'time period' (before, immediately after, and one year after the ALDFG removal). Sites served as replicates. Tukey's tests were conducted to identify differences in descriptor's values across station type and time period. Due to data heterogeneity in the upper layer descriptors, caused by an over-abundance of zero values where certain species were absent in some sites, ANOVA was deemed inadequate for our analysis. Thus, a Linear Mixed effects Model (LMM) was applied to assess before/after and control/impact effects as well as their interaction, on each upper layer descriptors (i.e., erect species).

All statistical analyses were performed using the software R-Studio (R Core Team, 2021) and PaSt (Hammer et al., 2001).

2.3.2. Coralligenous community composition

Presence/absence data of species recorded in the intermediate and upper layers of the coralligenous reefs were organised into a data matrix with dimensions [(time period × station type) × species]. For the 'time period' factor, three periods were considered: before ALDFG removal (B), immediately after (A), and one year after (O). For the 'station type' factor, two types were included: impact station (I) and control station (C). Sites served as replicates.

The data matrix was analysed using the Correspondence Analysis (CA) to assess changes in the composition of the coralligenous community immediately after ALDFG removal and after one year. To test for significant differences in community composition, a two-way permutational multivariate analysis of variance (PERMANOVA) was performed with the same model of univariate analyses, followed by a PAIRWISE test for significant terms.

3. Results

3.1. Retrieved fishing gears and entangled species

A total of 1 line, 7 nets, 41 fish traps and 2 ropes have been removed between July and September 2022 during the 'Cleaning coralligenous reefs from ALDFG in the Capo Carbonara MPA' project (Fig. 3, Table 1). The most abundant species found in the retrieved ALDFG were: the encrusting red algae *Lithophyllum stictaeforme*, which covered about 10 % of the total surface area of the retrieved ALDFG, and the erect red algae *Osmundaria volubilis,* whose cover at Punta Karalis reached 70 %; the erect bryozoans, which covered about 50 % of the total surface area of the ALDFG, mainly composed by the species *Pentapora fascialis*, *Smittina cervicornis*, and *Turbicellepora avicularis;* the gorgonians *Eunicella cavolini*, for which a total of 11 colonies were found entangled in the retrieved ALDFG, *Eunicella singularis*, with 4 colonies, *Leptogorgia sarmentosa*, with 2 colonies, and *Paramuricea clavata*, with 10 colonies entangled. The same data on the Dotti and Gorgonie sites were unfortunately not available.

Fig. 3. Fishing gears (nets, traps, and ropes) retrieved in the Capo Carbonara Marine MPA and dead colonies of *Eunicella cavolini* found entangled within them (Photos by Capo Carbonara MPA staff).

3.2. Ecological status of coralligenous reefs

The COARSE index revealed an overall good ecological status for the coralligenous reefs within the Capo Carbonara MPA at nearly all sites and stations (both control and impact), before (B) the ALDFG removal (Fig. 4, Table S3). The only exception was Punta la Guardia, where both control and impact stations showed a moderate status. Immediately following the ALDFG removal (A), the ecological status at the impact stations of Punta Karalis and Santa Caterina declined to a moderate level. However, within one year after the removal (O), both stations exhibited signs of recovery, with the ecological status returning to a good level (Fig. 4, Table S3). No changes in ecological status were observed over time at the other stations, with Punta la Guardia consistently remaining at a moderate status throughout the monitoring period.

Layer-specific analysis revealed different responses to ALDFG removal (Fig. 5, Table S4). The basal layer remained stable, with no declines in ecological status observed. In the intermediate layer, five impact stations experienced a decline in ecological status, with only partial recovery recorded one year later. The upper layer also showed declines at two impact stations, particularly at Capo Boi and Punta Karalis; and no recovery was observed after one year. Control stations generally maintained stability, except for Secca di Mezzo, where improvements in both the intermediate and upper layers were noted, due to reduced epibiosis and necrosis.

Two-way ANOVA revealed no significant differences between control and impact stations, nor across time periods, for the descriptors AN and TURF/SED cover (Table S5). In contrast, NCEA cover was significantly affected by time period ($p = 0.002$), and ECR was significantly influenced by the interaction between station type and time period ($p = 0.012$). The Tukey's test showed no statistically significant differences between any pair of station types within each time period (e.g., control after vs. control one year after), indicating that the basal layer descriptors did not vary significantly between station types, regardless of time. These results suggest that the removal of ALDFG had no measurable effect on this layer (Table S5). In the intermediate layer, species richness was significantly affected by removal ($p = 0.011$), with no significant impact from station type (Table S5). The Tukey's test revealed a change in species richness in the intermediate layer at impact stations, with a significant difference between the period before and after the removal of ALDFG ($p = 0.004$). However, no statistical differences were observed in control stations over time, or between impact stations after the removal and one year post-removal. In the upper layer, *Eunicella cavolini* was the most abundant gorgonian species, followed by *Paramuricea clavata* and *Eunicella singularis*. Linear Mixed Models (LMMs) indicated no statistically significant effect of ALDFG on the abundance of erect species overall (Table S6.1, S6.2, S6.3).

Table 1
Characteristics of the fishing gears that were measured upon retrieval, and the cover of entangled species that was visually assessed.

	Capo Boi			Punta Karalis				Punta la Guardia		Santa Caterina				Secca di Mezzo		
Gear type	Net	Net	Trap	Net	Net	Net	Net	Net	Rope	Net	Trap	Trap	Rope	Line	Net	Trap
Length (m)	15	130	29	26	25	25	50	30	20	20	5	6	50	25	15	1
Width (m)	–	–	0.4	1	1	1	0	0.2	–	–	0.45	1	–	–	–	0.45
Species cover (%)	70	60	75	75	70	80–85	40	70	0	60	0	0	80	0	85	0

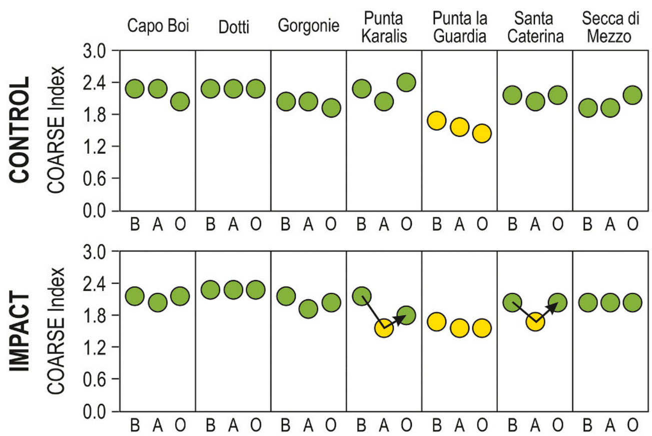

Fig. 4. COARSE Index scores (represented by circles) for the seven monitored sites in the Capo Carbonara MPA, at each station (control and impact), across the three time periods (B: before, A: immediately after, and O: one year after ALDFG removal). Colours indicate ecological status level (see Table S2): green represents good ecological status and yellow represents moderate ecological status. Changes in ecological status through time are highlighted with arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Coralligenous community composition

Correspondence Analysis (CA) showed no significant shifts in community composition across stations immediately after the ALDFG removal (Fig. 6). However, a possible time-related effect was observed along the first axis one year after removal, affecting both control and impact stations.

PERMANOVA confirmed significant temporal changes in community composition ($p = 0.009$), while neither station type (control vs. impact, $p = 0.885$) nor the interaction between time period and station type ($p = 0.996$) showed significant effects (Table S7). Consistently, the PAIRWISE test highlighted significant differences among one year after (O) and the other time periods (B and A) (Table S8).

4. Discussion

The removal of abandoned, lost, or discarded fishing gear (ALDFG) remains a highly debated issue. While the goal is to protect the marine environment, it is not always guarantee that ALDFG removal is the most effective strategy (Ruitton et al., 2019, 2020). For instance, when ALDFG has been on the seafloor for an extended period, it may have already become colonized by a variety of species, including those of high conservation priority (Costa et al., 2024). In such situations, removing the gear could inadvertently cause further damage, disrupting established ecological relationships and potentially leading to greater ecological impacts.

The new protocol outlined in this study allowed to investigate the effect of ALDFG removal on the coralligenous reefs of the Capo Carbonara MPA. The ecological status of these habitats was compared before, immediately after, and one year after the ALDFG removal by applying the COARSE ecological index (Gatti et al., 2012, 2015). A subsequent analysis of the coralligenous community composition was conducted to offer a more comprehensive understanding of the ecological changes resulting from ALDFG removal, as well as the recovery capacity of coralligenous reefs following mechanical disturbance. Application of the COARSE index showed an overall good ecological status of the coralligenous reefs in the before period. After the removal of ALDFG, a reduction to a moderate ecological status was observed for two out of the seven sites monitored. As a first hypothesis, this could be due to organisms that quickly overgrow on ALDFG (e.g., encrusting and erect bryozoans, encrusting corallinales, erect algae, *Peyssonnelia* spp.) that increase the specific richness in a given habitat, as it happens with artificial substrates (Ostalé-Valriberas et al., 2018). These organisms are inevitably removed together with the ALDFG (Moschino et al., 2019). Of course, this does not imply that ALDFG enhances the biodiversity of a given area. While ALDFG may provide artificial substrates for species that colonize them, they also suffocate and contribute to the death of many organisms that become entangled or covered (Norris et al., 2011; Ruitton et al., 2019). As a positive outcome, the coralligenous reefs ecological status at both impact sites showed recovery one year after the removal of ALDFG, returning to a good ecological status similar to that observed before the gear's removal.

A better understanding of the effect of ALDFG removal on the coralligenous habitat was obtained by analysing the three coralligenous layers (basal, intermediate, and upper) separately, both in the impact and control stations. Before the removal of the ALDFG, the basal layer showed either a high or a good ecological status in all the monitored sites, and in both control and impact stations, and no changes were observed over time after the removal of ALDFG on this layer. The species inhabiting the basal layer (mainly encrusting species, such as algae, bryozoans, and sponges) are less sensitive to mechanical damages than the erect species of the intermediate and the upper layers, although during the monitoring activities some bleached corallinales were observed, likely due to being covered by ALDFG. A similar effect has been described in coralligenous reefs affected by benthic mucilage (Piazzi et al., 2018) and a decrease of encrusting coralline algae is reported for coralligenous assemblages subjected to high sedimentation rate (Balata et al., 2005). These patterns suggest that the impact due to the presence of ALDFG may be comparable to that described for other alterations affecting this habitat and relate to a covering effect. Nevertheless, the analysis conducted on the cover of the basal layer descriptors (i.e., encrusting calcified Rhodophyta, non-calcified encrusting algae, encrusting animals, turf-forming algae and sediment) did not show significant differences between any pair of station types within each time period suggesting that ALDFG removal did not significantly affect the basal layer of the coralligenous habitat. It is worth highlighting that this could also be related to the size of the ALDFG, which may have covered only a limited area of the seafloor, and/or to their residence time, which may have been too short to suffocate a significant amount of the organisms below (Macfadyen et al., 2009; Ruitton et al., 2020; Enrichetti et al., 2021).

The intermediate layer showed the most significant response to ALDFG removal when comparing control and impact stations. In fact, a reduction in the ecological status from high/good to moderate was observed in five out of the seven impact stations monitored immediately after the ALDFG removal. In three of these stations, a recovery in ecological status was observed one year later. Moreover, the mean number of conspicuous species in the intermediate layer was

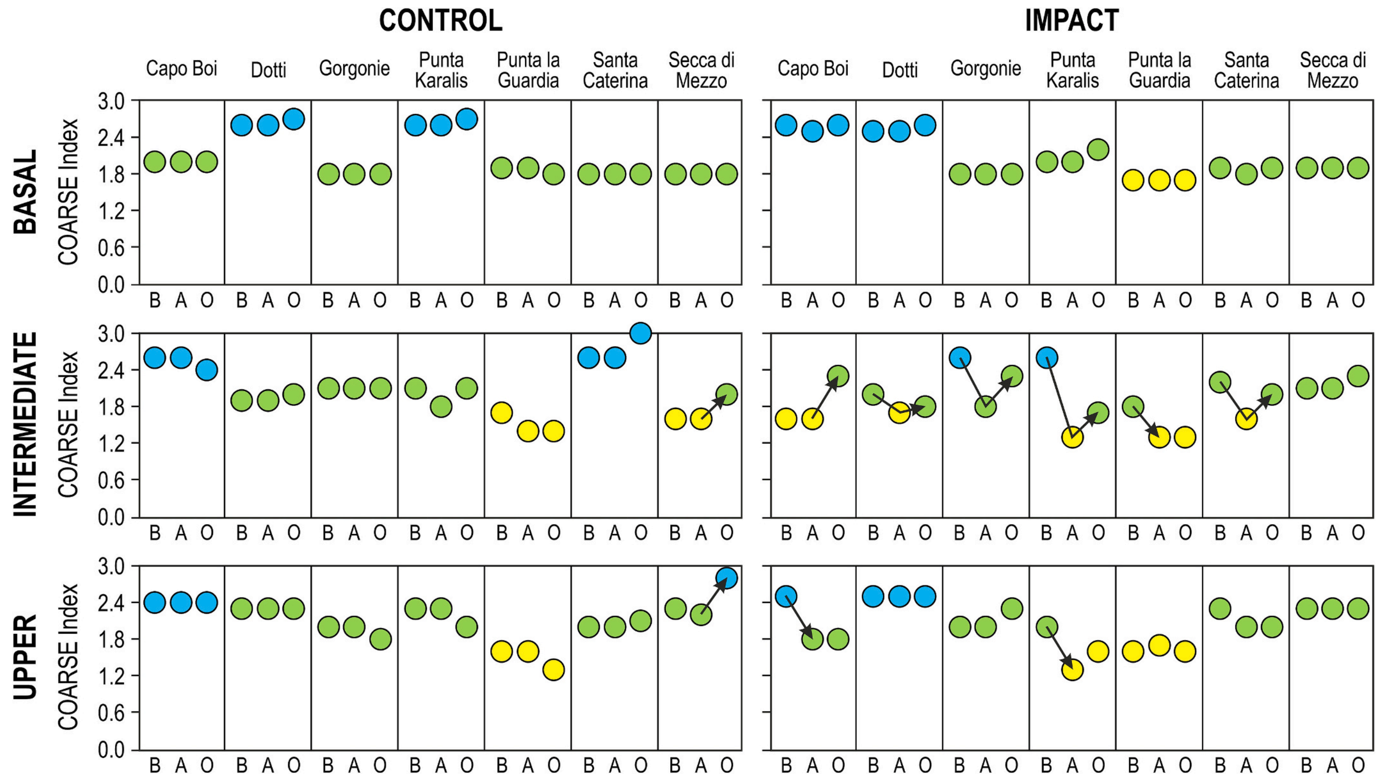

Fig. 5. COARSE Index scores for the coralligenous layers (basal, intermediate, and upper) of the seven monitored sites in the Capo Carbonara MPA, at each station (control and impact), across the three time periods (before, immediately after, and one year after ALDFG removal). Colours indicate ecological status level (see Table S2): blue represents high ecological status, green represents good ecological status, and yellow represents moderate ecological status. Changes in ecological status through time are highlighted with arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

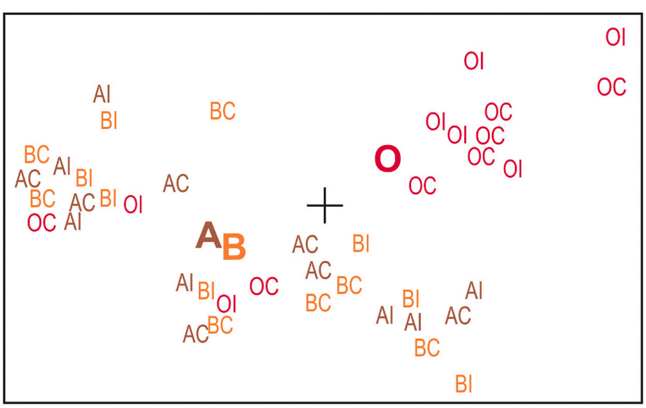

Fig. 6. Correspondence Analysis (CA) plot of the Capo Carbonara MPA monitored stations represented by alphabetic codes, with the time period (B: before ALDFG removal in orange; A: immediately after the removal in brown; O: one year after the removal in red), followed by the station type (C: control; I: impact). Centroids of the replicates for each time period are in bold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significantly affected by time period, which number decreased from 9 to 7 after the removal in the impact stations and then increased to 8 one year later. This is confirmed by the qualitative observation done on the retrieved ALDFG, where the most abundant entangled species were bryozoans, filamentous algae and *Osmundaria pelagosae*, all erect species that characterise the intermediate layer of the coralligenous habitat.

An overall high or good ecological status resulted from the upper layer of the coralligenous reefs (apart for Punta la Guardia, where it was moderate). A reduction in ecological status was observed at two impact stations immediately after the ALDFG removal. Due to their three-dimensional structure, gorgonians that characterise the upper layer of coralligenous habitat are among the most vulnerable to the impact of ALDFG, making them particularly prone to entanglement (Giusti et al., 2019; Betti et al., 2020). However, in the present study the abundance of gorgonians did not significantly change over time, and the observed reduction in ecological status can be mainly attributed to a reduction in their height. For both impact stations, no recovery in ecological status was observed one year later. In contrast, an improvement in the ecological status of the upper layer at Secca di Mezzo was noted, attributed to a reduction in gorgonian epibiosis and necrosis.

Overall, the intermediate and upper layers were the most affected by ALDFG removal and should therefore be prioritized during such operations. Minor changes in species abundance were detected, consistent with the community composition analysis, which revealed little change before and immediately after ALDFG removal, followed by a significant shift one year later. This community shift might be due to a combination of natural and anthropogenic pressures, which can occur in addition to the impact of ALDFG. The fact that both control and impact stations showed similar trends clearly suggests that the observed changes are not attributable to ALDFG removal, but rather to an 'outside effect', which is unfortunately difficult to identify. However, the analysis on each COARSE index descriptor (each of which responds differently to pressures) and community composition raised hypotheses about the role of climate change in this community shift. A decline in the abundance of gorgonians and bryozoans between 2016 and 2020 following heat waves has already been reported in the Capo Carbonara MPA (Piazzi et al., 2018, 2021). Similarly, rocky reef communities within this protected area have experienced significant changes over the past 20 years, primarily driven by seawater warming (Azzola et al., 2022). All these additional factors may have blurred the analysis on the effects of ALDFG removal, as well as could have slowed down or reduced the coralligenous habitat recovery capacity in the short time. Considering the slow growth rate of many coralligenous species, it would be advisable to extends monitoring efforts over a longer time frame in the future.

Preliminary analyses on the areas affected by ALDFG are essential to determine whether removal actions should be conducted or not. An existing robust approach for assessing the effects of ALDFG and determining the most appropriate removal strategy (Ruitton et al., 2019, 2020) considers factors such as the scale of the impact, the size and type of fishing gear, and information about species that colonized or became trapped in the nets. Notwithstanding these considerations, the new protocol proposed in this study proved successful in assessing the impact of ALDFG removal on the coralligenous habitat. The application of the protocol, employing divers, is limited to shallower coralligenous reefs, but most of ALDFG involves deeper reefs (Bo et al., 2014; Ferrigno et al., 2018b; Enrichetti et al., 2019a) where monitoring and removal activities are normally conducted by ROV. However, the approach followed to develop the protocol described in this paper may potentially also be valid for deeper coralligenous reefs, by appropriately modifying sampling methods and descriptors, for example by using ROV and applying MACS Index (Mesophotic Assemblages Conservation Status; Enrichetti et al., 2019b).

The monitoring activities carried out at Capo Carbonara MPA are an effective example of how the ALDFG removal is recommended when it is done by trained operators and in a way that does not create further damages on the sessile communities. In addition to its natural value, coralligenous habitat also has an aesthetic and economic value, as it represents an attractive for divers (Rodrigues et al., 2016). The maintenance of the seascape integrity, which also includes the cleaning of ALDFG, must be widely considered in the conservation activities of any MPA.

CRediT authorship contribution statement

Annalisa Azzola: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Pelizza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Fabrizio Atzori:** Resources, Project administration, Funding acquisition. **Viola Maria Atzeni:** Writing – review & editing, Resources, Investigation, Data curation. **Nicoletta Cadoni:** Writing – review & editing, Resources, Investigation, Data curation. **Lara Carosso:** Writing – review & editing, Resources, Investigation, Data curation. **Maria Leonor Garcia Gutiérrez:** Writing – review & editing, Resources, Investigation, Data curation. **Ilaria Mancini:** Writing – review & editing, Resources, Investigation, Data curation. **Chiara Paoli:** Writing – review & editing, Validation, Resources, Funding acquisition. **Luigi Piazzi:** Writing – review & editing, Validation, Resources, Investigation, Formal analysis, Data curation. **Monica Montefalcone:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Funding sources

This work was supported by the Blue Marine Foundation and Fondazione Capellino.

Declaration of competing interest

Fabrizio Atzori reports that financial support was provided by Blue Marine Foundation and Fondazione Capellino. The other 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.

Acknowledgements

The authors would like to thank Blue Marine Foundation and Fondazione Capellino for funding the project, Carlo Nike Bianchi and Carla Morri for their scientific advice, and Egidio Trainito for the photos in Fig. 2. The removal of the ALDFG was carried out by the Carabinieri Diving Unit of Cagliari, together with professional divers from the "Mari Nostrum" association, and thanks to the logistical support of the fisherman Silverio Sandalo.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118004.

Data availability

Data will be made available on request.

References

Angiolillo, M., Fortibuoni, T., 2020. Impacts of marine litter on Mediterranean reef systems: from shallow to deep waters. Front. Mar. Sci. 7, 581966. https://doi.org/10.3389/fmars.2020.581966.

Appolloni, L., Bevilacqua, S., Sbrescia, L., Sandulli, R., Terlizzi, A., Russo, G.F., 2017. Does full protection count for the maintenance of β-diversity patterns in marine communities? Evidence from Mediterranean fish assemblages. Aquat. Conserv. 27 (4), 828–838. https://doi.org/10.1002/aqc.2750.

Auster, P.J., Langton, R.W., 1999. The effects of fishing on fish habitat. In American Fisheries Society Symposium 22, 150–187.

Azzola, A., Atzori, F., Bianchi, C.N., Cadoni, N., Frau, F., Mora, F., Morri, C., Oprandi, A., Orrù, P.E., Montefalcone, M., 2022. Variability between observers does not hamper detecting change over time in a temperate reef. Mar. Environ. Res. 177, 105617. https://doi.org/10.1016/j.marenvres.2022.105617.

Azzola, A., Mancini, I., Montefalcone, M., 2023. Cleaning Coralligenous Reefs from Abandoned Fishing Gears in Capo Carbonara Marine Protected Area - Final Report after One Year. University of Genova, DiSTAV.

Balata, D., Piazzi, L., Cecchi, E., Cinelli, F., 2005. Variability of Mediterranean coralligenous assemblages subject to local variation in sediment deposits. Mar. Environ. Res. 60, 402–421.

Ballesteros, E., 2006. Mediterranean coralligenous assemblages: a synthesis of present knowledge. Oceanogr. Mar. Biol. Annu. Rev. 44, 123–195.

Bavestrello, G., Cerrano, C., Zanzi, D., Cattaneo-Vietti, R., 1997. Damage by fishing activities to the gorgonian coral *Paramuricea clavata* in the Ligurian Sea. Aquat. Conserv. 7 (3), 253–262. https://doi.org/10.1002/(sici)1099-0755(199709)7:3.

Betti, F., Bavestrello, G., Bo, M., Ravanetti, G., Enrichetti, F., Coppari, M., Cappanera, V., Venturini, S., Cattaneo-Vietti, R., 2020. Evidences of fishing impact on the coastal gorgonian forests inside the Portofino MPA (NW Mediterranean Sea). Ocean Coast. Manag. 187, 105105. https://doi.org/10.1016/j.ocecoaman.2020.105105.

Bo, M., Bava, S., Canese, S., Angiolillo, M., Cattaneo-Vietti, R., Bavestrello, G., 2014. Fishing impact on deep Mediterranean rocky habitats as revealed by ROV investigation. Biol. Conserv. 171, 167–176. https://doi.org/10.1016/j.biocon.2014.01.011.

Clark, M.R., Koslow, J.A., 2007. Impacts of fisheries on seamounts. In: Pitcher, T.J., Morato, T., Hart, P.J.B., Clark, M.R., Haggan, N., Santos, R.S. (Eds.), Seamounts: Ecology, Fisheries and Conservation. Blackwell Publishing. Blackwell Publishing, Oxford, UK, pp. 413–441.

Consoli, P., Romeo, T., Angiolillo, M., Canese, S., Esposito, V., Salvati, E., Scotti, G., Andaloro, F., Tunesi, L., 2019. Marine litter from fishery activities in the Western Mediterranean Sea: the impact of entanglement on marine animal forests. Environ. Pollut. 249, 472–481.

Costa, G., Manconi, R., Sanna, G., Arrostuto, N., Fois, N., Sechi, C., Tomassetti, P., Lomiri, S., 2024. Could some lost fishing gears be suitable substrata for benthic invertebrates? The case of some colonizer sponge assemblages in the Western Mediterranean Sea. Diversity 16 (9), 575. https://doi.org/10.3390/d16090575.

Do, H., Armstrong, C.W., 2023. Ghost fishing gear and their effect on ecosystem services – identification and knowledge gaps. Mar. Policy 150, 105528. https://doi.org/10.1016/j.marpol.2023.105528.

Enrichetti, F., Bava, S., Bavestrello, G., Betti, F., Lanteri, L., Bo, M., 2019a. Artisanal fishing impact on deep coralligenous animal forests: a Mediterranean case study of marine vulnerability. Ocean Coast. Manag. 177, 112–126. https://doi.org/10.1016/j.ocecoaman.2019.04.021.

Enrichetti, F., Bo, M., Morri, C., Montefalcone, M., Toma, M., Bavestrello, G., Tunesi, L., Canese, S., Giusti, M., Salvati, E., Bertolotto, R.M., Bianchi, C.N., 2019b. Assessing the environmental status of temperate mesophotic reefs: a new, integrated methodological approach. Ecol. Indic. 102, 218–229.

Enrichetti, F., Bavestrello, G., Betti, F., Rindi, F., Tregrosso, A., Bo, M., 2021. Fate of lost fishing gears: experimental evidence of biofouling colonization patterns from the northwestern Mediterranean Sea. Environ. Pollut. 268, 115746.

European Commission, 2008. Directive 2008/56/EC establishing a framework for community action in the field of marine environmental policy (marine strategy framework directive). Off. J. Eur. Union L164, 19–40.

European Parliament, 2024. Legislative resolution of 27 February 2024 on the proposal for a regulation of the European Parliament and of the Council on nature restoration COM(2022)0304 – C9–0208/2022–2022/0195(COD). Off. J. Eur. Union C/2004/6757.

Ferrigno, F., Russo, G.F., Sandulli, R., 2017. Coralligenous bioconstructions quality index (CBQI): a synthetic indicator to assess the status of different types of coralligenous habitats. Ecol. Indic. 82, 271–279.

Ferrigno, F., Russo, G.F., Semprucci, F., Sandulli, R., 2018a. Unveiling the state of some underexplored deep coralligenous banks in the Gulf of Naples (Mediterranean Sea, Italy). Reg. Stud. Mar. Sci. 22, 82–92. https://doi.org/10.1016/j.rsma.2018.05.006.

Ferrigno, F., Appolloni, L., Russo, G.F., Sandulli, R., 2018b. Impact of fishing activities on different coralligenous assemblages of gulf of Naples (Italy). J. Mar. Biol. Assoc. U. K. 98, 41–50.

Ferrigno, F., Appolloni, L., Donnarumma, L., Di Stefano, F., Rendina, F., Sandulli, R., Russo, G.F., 2021. Diversity loss in coralligenous structuring species impacted by fishing gear and marine litter. Diversity 13 (7), 331. https://doi.org/10.3390/d13070331.

Gatti, G., Montefalcone, M., Rovere, A., Parravicini, V., Morri, C., Albertelli, G., Bianchi, C.N., 2012. Seafloor integrity down the harbor waterfront: the coralligenous shoals off Vado Ligure (NW Mediterranean). Adv. Oceanogr. Limnol. 3 (1), 51–67.

Gatti, G., Bianchi, C.N., Morri, C., Montefalcone, M., Sartoretto, S., 2015. Coralligenous reefs state along anthropized coasts: application and validation of the COARSE index, based on a rapid visual assessment (RVA) approach. Ecol. Indic. 52, 567–576.

Gimenez, G., Pierri, C., Coccia, I., Longo, C., Marzano, C.N., Mercurio, M., 2022. Insights into the impact of marine litter on coralligenous structuring species in Apulia (Italy). 2022 IEEE international workshop on metrology for the sea; Learning to Measure Sea Health Parameters (MetroSea). https://doi.org/10.1109/metrosea55331.2022.9950846.

Giusti, M., Canese, S., Fourt, M., Bo, M., Innocenti, C., Goujard, A., Daniel, B., Angeletti, L., Taviani, M., Aquilina, L., Tunesi, L., 2019. Coral forests and derelict fishing gears in submarine canyon systems of the Ligurian Sea. Prog. Oceanogr. 178, 102186.

Golik, A., 1997. Debris in the Mediterranean Sea: types, quantities, and behavior. Marine debris: sources, impacts, and solutions 7-14. https://doi.org/10.1007/978-1-4613-8486-1_2.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PaSt: paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4, 4.

Macfadyen, G., Huntington, T., Cappell, R., 2009. Abandoned, lost or otherwise discarded fishing gear. FAO Fisheries and Aquaculture Technical Paper 523. http://enpa.sv.it/documenti/recuperiamo_le_reti_da_pesca_abbandonate.pdf.

Martin, C., Giannoulaki, M., De Leo, F., Scardi, M., Salomidi, M., Knittweis, L., Pace, M. L., Garofalo, G., Gristina, M., Ballesteros, E., Bavestrello, G., Belluscio, A., Cebrian, E., Gerakaris, V., Pergent, G., Pergent-Martini, C., Schembri, P.J., Terribile, K., Rizzo, L., Ben, Souissi J., Bonacorsi, M., Guarnieri, G., Krzelj, M., Macic, V., Punzo, E., Valavanis, V., Fraschetti, S., 2014. Coralligenous and maërl habitats: predictive modelling to identify their spatial distributions across the Mediterranean Sea. Sci. Rep. 4, 5073. https://doi.org/10.1038/srep05073.

Melli, V., Riginella, E., Nalon, M., Mazzoldi, C., 2014. From trap to nursery. Mitigating the impact of an artisanal fishery on cuttlefish offspring. PLoS One 9 (2), e90542.

Moschino, V., Riccato, F., Fiorin, R., Nesto, N., Picone, M., Boldrin, A., Da Ros, L., 2019. Is derelict fishing gear impacting the biodiversity of the northern Adriatic Sea? An answer from unique biogenic reefs. Sci. Total Environ. 663, 387–399.

Norris, N.J., Defoe, J., Ishida, M., John, S., Barbuda, A., 2011. Ghost fishing by lost and derelict fish pots in the commonwealth of Dominica. Proceedings of the 63rd Gulf and Caribbean fisheries institute (GCF 63), San Juan, Puerto Rico. November 1-4, 2010.

Orrù, P., Panizza, V., Ulzega, A., 2005. Submerged geomorphosites in the marine protected areas of Sardinia (Italy): assessment and improvement. Il Quaternario 18 (1), 167–174.

Ostalé-Valriberas, E., Sempere-Valverde, J., Coppa, S., García-Gómez, J.C., Espinosa, F., 2018. Creation of microhabitats (tidepools) in ripraps with climax communities as a way to mitigate negative effects of artificial substrate on marine biodiversity. Ecol. Eng. 120, 522–531.

Piazzi, L., Gennaro, P., Balata, D., 2012. Threats to macroalgal coralligenous assemblages in the Mediterranean Sea. Mar. Pollut. Bull. 64 (12), 2623–2629.

Piazzi, L., Atzori, F., Cadoni, N., Cinti, M.F., Frau, F., Ceccherelli, G., 2018. Benthic mucilage blooms threaten coralligenous reefs. Mar. Environ. Res. 140, 145–151.

Piazzi, L., Gennaro, P., Montefalcone, M., Bianchi, C.N., Cecchi, E., Morri, C., Serena, F., 2019. STAR: an integrated and standardized procedure to evaluate the ecological status of coralligenous reefs. Aquat. Conserv. Mar. Freshwat. Ecosyst. 29 (2), 189–201.

Piazzi, L., Atzori, F., Cadoni, N., Cinti, M.F., Frau, F., Pansini, A., Pinna, F., Stipcich, P., Ceccherelli, G., 2021. Animal forest mortality: following the consequences of a gorgonian coral loss on a Mediterranean coralligenous assemblage. Diversity 13 (3), 133. https://doi.org/10.3390/d13030133.

Piazzi, L., Gennaro, P., Azzola, A., Cinti, M.F., Montefalcone, M., 2025. Advancing Star: a revised protocol for assessing the ecological status of Coralligenous cliffs. Mar. Pollut. Bull. 213, 117684.

Pinna, F., Ragazzola, F., Piazzi, L., Evans, D., Raddatz, J., Ceccherelli, G., 2024. Crustose coralline algae exhibit complex responses to breakage under current and future climate scenarios. Mar. Pollut. Bull. 209, 117219.

R Core Team, 2021. A Language and Environment for Statistical Computing. Vienna, Austria, R Foundation for Statistical Computing.

Richardson, K., Hardesty, B.D., Vince, J., Wilcox, C., 2022. Global estimates of fishing gear lost to the ocean each year. Science. Advances 8 (41), eabq0135. https://doi.org/10.1126/sciadv.abq0135.

Rodrigues, L.C., van den Bergh, J.C., Loureiro, M.L., Nunes, P.A., Rossi, S., 2016. The cost of Mediterranean Sea warming and acidification: a choice experiment among scuba divers at Medes Islands. Spain. Environmental and Resource Economics 63 (2), 289–311.

Ruitton, S., Belloni, B., Marc, C., Boudouresque, C.F., 2019. Ghost Med: Assessment of the Impact of Lost Fishing Gear in the French Mediterranean Aea. Hal (Le Centre Pour La Communication Scientifique Directe). https://hal.science/hal-02112113.

Ruitton, S., Belloni, B., Boudouresque, C.F., Marc, C., Thibault, D., 2020. Methodological Guide for the Assessment of the Impacts of Derelict Fishing Gear, 2nd edition. M I O publ, p. 46.

Saldanha, H.J., Sancho, G., Santos, M.N., Puente, E., Gaspar, M.B., Bilbao, A., Monteiro, C.C., Gómez, E.D., Arregi, L., 2003. The use of biofouling for ageing lost nets: a case study. Fish. Res. 64 (2–3), 141–150. https://doi.org/10.1016/s0165-7836(03)00213-3.

Sheehan, E.V., Rees, A., Bridger, D., Williams, T., Hall-Spencer, J.M., 2017. Strandings of NE Atlantic gorgonians. Biol. Conserv. 209, 482–487. https://doi.org/10.1016/j.biocon.2017.03.020.

Stevens, B.G., 2020. The ups and downs of traps: environmental impacts, entanglement, mitigation, and the future of trap fishing for crustaceans and fish. ICES J. Mar. Sci. 78 (2), 584–596. https://doi.org/10.1093/icesjms/fsaa135.

Underwood, A.J., 1992. Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. J. Exp. Mar. Biol. Ecol. 161, 145–178.

Underwood, A.J., 1997. Experiments in Ecology: Their Logical Design and Interpretation Using Analysis of Variance. Cambridge University Press, p. 503.

Williams, A., Schlacher, T.A., Rowden, A.A., Althaus, F., Clark, M.R., Bowden, D.A., Stewart, R.A., Bax, N.J., Consalvey, M., Kloser, R., 2010. Seamount megabenthic assemblages fail to recover from trawling impacts. Mar. Ecol. 31 (1), 183–199. https://doi.org/10.1111/j.1439-0485.2010.00385.x.