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To GRaB or not to GRaB: a citizen science-based, decision-making index to assess the biological implications of lost fishing gears retrieval

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ABSTRACT

Abandoned, lost, or otherwise discarded fishing gears (ALDFGs) represent a major threat to marine biodiversity, yet their removal remains controversial when entangled with sensitive benthic communities. This study presents a standardized marine citizen science (MCS) protocol and a novel decision-making index, the Gear Removal-Biological (GRaB) index, designed to assess the ecological risks of ALDFG removal. Experienced volunteer divers applied the "Reef Alert Network (RAN) - Assessment of lost fishing gear" protocol to survey ALDFGs at coralligenous sites between 29 and 51 m depth in the Portofino Marine Protected Area (Italy), recording site characteristics, gear type, colonization levels, and taxa affected. A total of 91 ALDFGs were documented across 350 m^2, impacting nearly 1000 organisms, with the red gorgonian *Paramuricea clavata* being the most affected. The GRaB index integrates five indicators (Entangled Organisms, Surrounding Diversity, Biofouling Colonization, Habitat Complexity, and ALDFG Characteristics) to produce a simple traffic-light classification of low, medium, or high ecological risk. Tested on over 200 surveys, the index provided reliable estimates of potential harm, supporting informed decisions on whether removal should proceed and whether expert consultation is required. Beyond its scientific utility, the approach enhances MCS initiatives by empowering divers and stakeholders, raising awareness of fishing and ALDFG impacts, and providing managers with an adaptive tool transferable across Mediterranean habitats. Ultimately, this integrative framework promotes responsible retrieval practices while fostering collaborative governance, contributing to marine conservation, biodiversity restoration, and the sustainability goals of the UN Ocean Decade.

1. Introduction

Marine litter (i.e., solid waste produced by humans; UNEP, 2009) represents one of the main threats to marine communities, causing degrading effects to sessile, vagile and pelagic species (Bergmann et al., 2015), as well as to terrestrial organisms which rely on the sea for their diet (e.g., seabirds, sea lions, polar bears) (Bergmann et al., 2017; O'Hanlon et al., 2017). Together with plastic, abandoned, lost or otherwise discarded fishing gears (ALDFGs) are the main component of marine litter (Danovaro et al., 2025). ALDFGs are made almost exclusively of synthetic materials (Macfadyen et al., 2009) and once lost, they can trap vagile fauna, suffocate the benthos or abrade the seabed for

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decades (Angiolillo and Fortibuoni, 2020). It has been estimated that the annual gear loss rates up to almost 80% (Richardson et al., 2019), and that the costs of losing fishing gear do not only directly impact the fishermen investments (~4000 € for each pot/net lost; Drakeford et al., 2023), but also indirectly harm tourism and the ecosystem services usually provided by healthy marine communities (Do and Armstrong, 2023; Unsbo et al., 2023). Due to these aspects, ALDFGs are currently listed in Article 17 of the European Habitat Directive (92/43/EEC, pressure code PG13; Di Camillo et al., 2023), making urgent the need to collect data on their distribution and related impacts, as well as their careful removal from the seafloor. However, ALDFGs removal is often controversial, especially when it is performed by volunteers or professional divers without a scientific background, and/or when they have already provided a suitable substrate for benthic organisms (Costa et al., 2024; Drinkwin et al., 2022).

Marine Citizen Science (MCS) can represent a powerful tool in clean-up events (Bergmann et al., 2015), but the removal of ALDFGs from the seafloor by divers poses different challenges. Retrieval decisions typically depend on several factors, including the type of gear, its estimated weight and spatial extent, the material composition, and the time required for removal, as well as operational considerations such as the number and experience level of divers involved. Environmental and safety conditions (i.e., depth, current strength, and visibility), also strongly influence the feasibility and risks associated with such operations (Jimenez and Resaikos, 2025). More importantly, ALDFG removal strategies should account for potential impacts on benthic communities directly underlying or in close proximity to the entangled gear (Angiolillo and Fortibuoni, 2020). For this reason, interventions must only be conducted by highly skilled divers specifically trained in removal techniques. A careful selection of expert participants, followed by targeted training provided by scientists on best practices for approaching ALDFGs, is essential to minimize further damage and avoid potentially fatal impacts on already stressed organisms (Azzola et al., 2025; Gilardi et al., 2010).

A great example of a well-established and implemented MCS initiative occurs in the Portofino Marine Protected Area (MPA), where the *Conservation Diver* project was launched thanks to the continuous efforts of the non-profit organization Reef Alert Network (RAN) (Coppari et al., 2024). Since its designation as MPA in 1998, the presence and the impact of ALDFGs are known and documented (Azzola et al., 2021; Bavestrello et al., 1998; Betti et al., 2020; Enrichetti et al., 2019, 2020, 2021, 2023; Jacobsen et al., 2024; Markantonatou et al., 2014; Prato et al., 2016; Valisano et al., 2019; Venturini et al., 2017, 2019). Although fishing activities are regulated in the area, artisanal fishery is allowed inside the general and partial protection zones of the MPA (Betti et al., 2020; Venturini et al., 2019), making the ALDFGs still a reality. Additionally, when combined with the effects of the current climate crisis (Garrabou et al., 2022b; Vezzulli et al., 2013), they compromise the ecological and aesthetic values of the coralligenous communities of the area (Markantonatou et al., 2014), deeply affecting the natural capital of the MPA (over €10 million in 2018; Paoli et al., 2018) and calling for the need of adaptive management strategies addressing the issue.

In recent years, various ecological indexes have been proposed to evaluate the impacts of ALDFGs on marine ecosystems and to guide gear retrieval efforts. However, the existing indices are narrowly centred on specific taxonomic groups or overly generalized, resulting in insufficient attention to key ecological species. For example, Gilman et al. (2021) focused entirely on gears characteristics, developing an index on gear-specific risks, ranking fishing methods based on derelict gear production rates and adverse consequences. Rodríguez et al. (2025) placed emphasis just on marine megafauna (i.e., sharks, cetaceans, sea turtles and seabirds) found entangled by the assessed fishing-related items. Conversely, Ruitton et al. (2020) proposed a more comprehensive index (called GRI), but its broad approach dilutes the weight of critical habitat formers affected by ALDFGs. Similarly, Jimenez and Resaikos (2025) slightly modified Ruitton's approach by adapting the GRI index incorporating region-specific ecological considerations. All these examples, however: (i) fail to account for the functional importance of benthic habitat formers, a factor that is critical for understanding the full scope of ecosystem degradation caused by ALDFGs (Angiolillo and Fortibuoni, 2020; Azzola et al., 2025); and (ii) are intended for scientists, often limiting their application to experts in the field.

Within the *Conservation Diver* project, we developed a science-based protocol that is easy-to-apply and replicate for assessing the impact of ALDFGs, with a special emphasis on Mediterranean coralligeous assemblages. Additionally, we employed a multi-criteria approach (Hu et al., 2004) to create a user-friendly decision-making index for evaluating the potential biological impact associated with the hypothetical gear removal. The approaches here presented draw more attention to the biotic component, helping to prevent reckless recovery that could potentially cause further harm to benthic communities, especially in fragile contexts as those of MPAs. More specifically, the implemented index is intended to be calculated directly by users, providing an auto-filling Excel file; in any case, the oversight and/or consultancy of an expert marine biologist is strongly suggested.

Even though implemented mainly for coralligenous habitats, the proposed protocol and index allow their applicability to other localities and habitats/species across the ocean basin. The collected data will support the development of adaptive co-management strategies, raise awareness among fishermen, managers, the general public and policymakers, potentially inspiring the implementation of similar actions also beyond the Mediterranean Sea.

2. Materials and methods

2.1. Reef Alert Network (RAN): the Conservation Diver program and the "RAN-assessment of lost fishing gear" protocol

RAN is a non-profit organization (www.reefalert.org), supporting marine-habitat monitoring and restoration. In partnership with the Polytechnic University of Marche (Italy), it runs the *Conservation Diver* program, which applies citizen-science protocols for Mediterranean target species (e.g., MPA Engage, Reef Check Med) (Garrabou et al., 2022a; Turicchia et al., 2021). Volunteer divers receive training from marine biologists through seminars and goal-oriented dives (Coppari et al., 2024).

Among the activities included in the *Conservation Diver* program, the "RAN-Assessment of lost fishing gear" protocol was implemented and validated by RAN in collaboration with researchers from the Polytechnic University of Marche, University of Genoa and the Portofino MPA staff. The protocol was implemented mainly for coralligenous assemblages (being the mostly impacted by ALDFGs; e.g., Angiolillo and Fortibuoni, 2020; Azzola et al., 2025), considering the habitat-forming species typical in coralligenous habitats and mostly vulnerable to ALDFGs' damage (Angiolillo and Fortibuoni, 2020; Betti et al., 2020; Di Camillo et al., 2023). The protocol allows the collection of various information regarding the monitored site (i.e., site name, latitude and longitude, habitat type, inclination of the substrate, depth), the characteristics of the assessed ALDFG (i.e., type of gear, whether it is attached to the bottom, easy/difficult to remove, the presence of trapped mobile fauna, and the level of colonization) (Fig. S1A), and a list of the potentially impacted organisms, their abundance (divided in six categories) and the type of damage (i.e., entangled, broken, stripped) (Fig. S1B and S2; File S1).

2.2. ALDFGs assessments using the "RAN-assessment of lost fishing gear" protocol

The first extensive application of the RAN protocol occurred from the 18th to the 21st of April 2024 by 11 RAN volunteers inside the boundaries of the Portofino MPA, under the supervision of the MPA staff. All

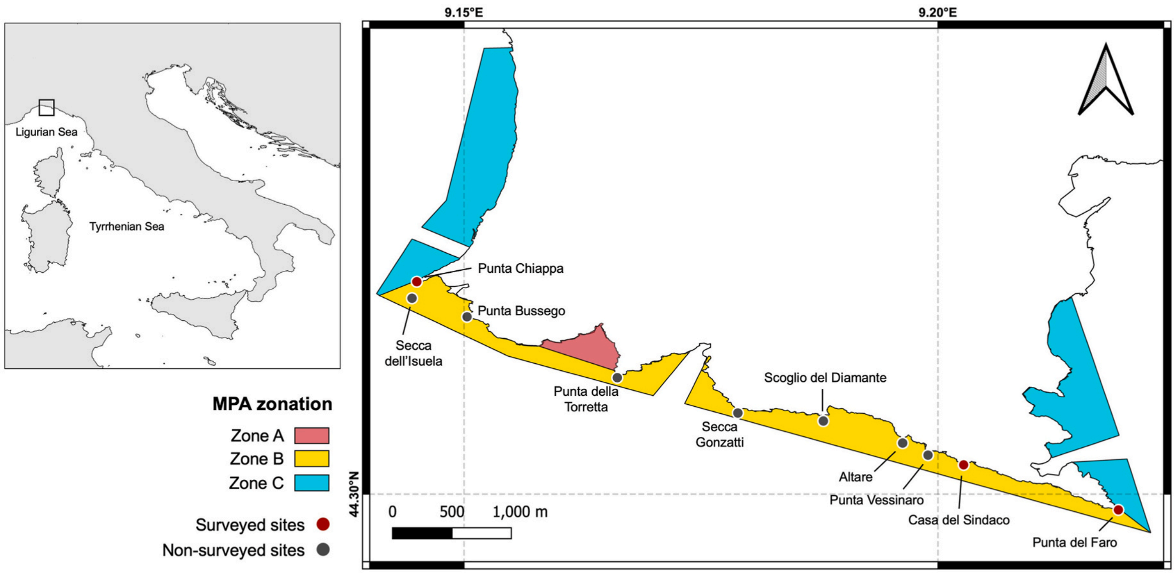

Fig. 1. Map of the location of the Portofino Marine Protected Area (MPA), highlighting the main capes of zone B interested by artisanal and recreational fishing activities, indicated by the circles.

volunteers taking part to the activities were experienced technical divers, each with more than 2000 logged dives, and already familiar with the protocol, having participated in previous *Conservation Diver* initiatives.

The Portofino MPA includes a total area of about 3.46 km^2 and presents the typical zonation of a protected area, comprehensive of a zone A of strict reserve, a zone B of general reserve and a zone C of partial reserve (https://www.portofinoamp.it). Activities were conducted during 8 technical dives between 29 and 51 m depth in the coralligenous habitats of three sites located in the zone B: Casa del Sindaco (44°18′11.1"N 9°12′09.3"E), Punta del Faro (44°17′54.0"N 9°13′08.2"E) and Punta Chiappa (44°19′20.5"N 9°08′41.5"E) (Fig. 1). Following an opportunistic survey method, all ALDFGs found in the three sites were assessed applying the RAN protocol and tagged (Fig. S2).

Data were extrapolated from all slates with the RAN protocol filled by volunteers and plots were created with R version 4.3.2 using the package *ggplot2* for bar-plots and donut charts, and the package *ggalluvial* for the alluvial diagram (R Core Team, 2024). Two experimental designs were created to look for differences in: i) the abundance of taxa

Table 1
Indicators used to calculate the Gear Removal-Biological index (GRaB), together with the target and description of each indicator.

Indicator	Targets	Description
I. Entangled organisms (EO)	Low vulnerability: 1. Corallinales 2. Bryozoa Moderate vulnerability: 3. Ircinidae 4. *Axinella* spp. 5. *Eunicella cavolini* 6. *E. singularis* 7. *E. verrucosa* 8. *Leptogorgia sarmentosa* High vulnerability: 9. *Paramuricea clavata/Savalia savalia* Very high vulnerability: 10. *Corallium rubrum* 11. *Pinna* spp.	Sum of the total number of entangled organisms, considering their morpho-functional traits (i.e., massive/erected habits, fragility of the skeleton) (Ballesteros, 2003, 2006)
II. Surrounding diversity (SD)	Corallinaceans, Bryozoa, *Axinella* spp., *Eunicella cavolini, E. singularis, E. verrucosa, Paramuricea clavata, Leptogorgia sarmentosa, Savalia savalia, Corallium rubrum, Pinna nobilis*	Sum of empirical abundance classes of all taxa detected surrounding the ALDGF. Classes were attributed based on morpho-functional traits and vulnerability level (i.e., size, level of protrusion from the substrate, lifespan, modularity, fragility of the skeleton, and growth rates) (Ballesteros, 2003, 2006); large, long-living and slow-growing organisms obtain the highest scores
III. Biofouling colonization (BC)	Calcified/non-calcified colonizers (i. e., bryozoans, sponges, tunicates, polychaetes, ect.)	Estimated percentage cover and type of biofouling species in relation to the ALDFG type. For carbonatic colonizers, the score is doubled. The highest value achievable by the metrics is 30
IV. Habitat (Hb)	Coralligenous, *Posidonia ocenica* meadows, wrecks, detritic bottoms	Sum of the scores of: a. Habitat type classified considering their vulnerability to ALDFGs (based on Ruitton et al. (2020); Angiolillo and Fortibuoni (2020)); b. Attachment of the ALDFG to substrate; c. Inclination of substrate (degree of inclination), with vertical walls obtaining the highest scores
V. ALDFG (FG)	Gear type (i.e., Weights, lures, hooks, ropes, lines, nets, trawl nets)	Gear types are classified by the destructive potential to benthic communities (Azzola et al., 2025; Bo et al., 2014; Perry et al., 2022)

Table 2
Detailed calculation of each indicator for the evaluation of Gear Removal-Biological index (GRaB).

Indicator	Criteria	Taxon	Number of entangled organisms (NEO)		Morpho-functional traits		Calculation	Final score	
			Options	Score (A)	Options	Score		Options	Score
I. Entangled organisms (EO)	Taxonomic group	Corallinales	NEO = 0	0	Massive/Erected carbonatic organisms (**B**)	1	**EO = A + B + C**	EO ≤ 5	EO
		Bryozoans	1≤NEO≤5	1	Massive/Erected non-carbonatic organisms (**C**)	0.5			
		Ircinidae	5≤NEO≤15	2					
		Axinella spp.	16≤NEO≤30	3					
		Eunicella singularis	NEO≥31	4					
		Eunicella cavolinii						EO > 5	5
		Eunicella verrucosa							
		Lepotogorgia sarmentosa							
		Paramuricea clavata/ Savalia savaglia							
		Corallium rubrum							
		Pinna spp.							

Indicator	Criteria	Taxa	Abundance classes		Calculation	Final score	
			Options	Score (D)		Options	Score
II. Surrounding diversity (SD)	Abundance classes	1. Corallinales 2. Bryozoans	A) one isolated individual	0.1	$\mathbf{SD} = \sum_{i=1}^{11} \mathbf{D}$	SD ≤ 5	SD
			B) some scattered individuals	0.2			
			C) several scattered individuals	0.5			
			D) one crowded area	0.75			
			E) some crowded areas	1			
			F) several crowded areas	1.25			
		3. Ircinidae 4. *Axinella* spp. 5. *Eunicella singularis* 6. *Eunicella cavolini* 7. *Eunicella verrucosa* 8. *Lepotogorgia sarmentosa*	A) one isolated individual	0.1			
			B) some scattered individuals	0.2			
			C) several scattered individuals	0.75			
			D) one crowded area	1			
			E) some crowded areas	1.5			
			F) several crowded areas	2			
		9. *Paramuricea clavata/Savalia savaglia*	A) one isolated individual	0.1		SD > 5	5
			B) some scattered individuals	0.2			
			C) several scattered individual	1			
			D) one crowded area	1.25			
			E) some crowded areas	2			
			F) several crowded areas	2.5			
		10. *Corallium rubrum* 11. *Pinna* spp.	A) one isolated individual	0.1			
			B) some scattered individuals	0.2			
			C) several scattered individuals	1.25			
			D) one crowded area	1.5			
			E) some crowded areas	2			
			F) several crowded areas	3			

Indicator	Criteria	Percentage of colonizers		Type of colonizers		Final score
		Options	Score (E)	Options	Score (F)	
III. Biofouling colonization (BC)	Percentage cover and type of biofouling species	Absent or low	0	Non-carbonatic organisms	0	**BC = [(E × J) + (E × F × J)/(30)] x 5**
		Moderate (<80 %)	1	Carbonatic organisms	**E** × 2	
		High (≥80 %)	2			

Indicator	Criteria	Percentage of colonizers		Inclination of the substrate (°)		Attachment of the ALDFG to the bottom		Final score
		Options	Score (G)	Options	Score (H)	Options	Score (I)	
IV. Habitat (Hb)	Habitat type	Detritic	1	0°–30°	0	Yes	1	**Hb = G + H + I**
		Wrecks	1.5	31°–60°	0.25			
		Posidonia oceanica	2.5	61°–90°	0.5	No	0	
		Coralligenous	3.5	>90°	0.75			

Indicator	Criteria	ALDFG	
		Type	Final Score (J)
V. ALDFG (FG)	ALDFG type	Weights, lures, hookes	1
		Rope	2
		Line	3
		Net	4
		Trawl net	5

among sites and ii) the number of organisms per taxa among damage types and sites. In the first experimental design, only one factor was considered: site (random, 3 levels: Casa del Sindaco, Punta del Faro, Punta Chiappa); for the second design, two crossed factors were instead considered: site (random, 3 levels: Casa del Sindaco, Punta del Faro, Punta Chiappa), damage (fixed, 3 levels: entangled, stripped, broken). Since the number of replicates per site is related to the number of ALDFGs found at each site, both experimental designs were unbalanced. Data of both designs were square-root transformed, then Permutational Analyses of Variance (PERMANOVA; Anderson, 2001) were performed using dissimilarity matrices based on the Bray-Curtis dissimilarity and setting 9,999 permutations and type III Sum of Squares. *A posteriori* pairwise comparison was conducted when significant differences occurred. Additionally, the analysis of similarity percentages (SIMPER; Clarke, 1993) was used to determine taxon contributions to the recorded dissimilarities. Statistical differences were considered when alpha = 0.05. Statistical analyses were conducted using the software PRIMER 7.0.20 (Clarke and Gorley, 2015) with the add-on PERMANOVA + (Anderson et al., 2008).

2.3. *The **Gear Removal-Biological** index (**GRaB**): design, implementation and validation*

GRaB is a decision-support, multi-metric index that estimates the expected biological damage to communities in contact, covered or near a specific ALDFG if that gear is removed. The index combines five indicators (Table 1) derived from the RAN protocol and it is applied to each observed gear item:

I. **Entangled organisms (EO)** — considers the total number of habitat-forming taxa directly in contact or covered with the assessed ALDFG.
II. **Surrounding diversity (SD)** — considers the abundance classes of all taxa detected surrounding the ALDGF, depending also on their morpho-functional traits and vulnerability to lost gears; this indicator accounts for the likelihood of harming healthy organisms during removal. Empirical abundance was preferred over density due to the potentially large population size of these organisms.
III. **Biofouling colonization (BC)** — percentage of the gear covered by calcified and/or non-calcified organisms; heavy colonization increases mass and handling difficulty. When derelict gear becomes extensively overgrown and interwoven with the surrounding habitat (Enrichetti et al., 2021), removal may cause more ecological harm than leaving it *in situ.*
IV. **Habitat (Hb)** — considers the type of impacted habitat (classified depending on their vulnerability to ALDFGs), the gear position relatively to the substrate (if attached and becoming embedded to the substrate or if not completely sink but elevated from the substrate), as well as the slope (degree of inclination of the substrate); risk of removal increases where the gear is attached to the substrate, especially on vertical walls.
V. **ALDFG (FG)** — considers different type of potentially lost fishing gears, classifying them depending on their destructive potential to benthic communities.

Each indicator can range from 0 to 5, each one contributing up to a 25% to the total of the index. For their calculation, scores were assigned the different metrics composing each indicator (please refer to Table 2 for a detailed description of the calculation).

The GRaB index corresponds to the sum of these scores:

$$\text{GRaB index} = \text{EO} + \text{SD} + \text{BC} + \text{Hb} + \text{FG}$$

where: EO = Entangled organisms, SD = Surrounding diversity, BC = Biofouling colonization, Hb = Habitat, and FG = ALDFG.

More specifically, a GRaB score (i) < 10 indicates a potential low impact to the community affected by and surrounding the ALDFG, (ii) 10–18 indicates a potential medium impact; (iii) > 18 indicates a potential high impact. The maximum score (GRaB = 25) occurs when the most vulnerable taxa (e.g., *Corallium rubrum/Pinna nobilis*), complex habitats (e.g., vertical coralligenous walls), and highly destructive gears (e.g., trawl nets) co-occur (Table 2). While gear removal with low GRaB scores does not require expert support, medium and high scores recommend or necessitate the involvement of marine biologists.

To facilitate uptake by stakeholders, a pre-filled spreadsheet mirroring the underwater slate is provided in the Supplementary Material (Table S1). The index is also visualised as a pentagonal radar plot whose axes represent the five indicators, with a traffic-light colour scale translating the GRaB score for communication with non-specialists. A companion table reports the score of each indicator and the total GRaB value.

The index was implemented and tested considering all surveys conducted applying the RAN protocol (over 200) from 2022 to 2025 on coralligenous assemblages in different localities: Portofino MPA, Punta Manara (Special Area of Conservation, code IT1333308), Santo Stefano shoal and Tremiti Island MPA. For each survey, consistency across photographs, videos, and collected data was assessed to determine whether the index accurately reflected the risk of removal. Six examples of the application of the proposed index are presented in the Results section to illustrate a gradient of the GRaB index score; a traffic light icon was used to define three scenarios: (i) red light, corresponding to "high impact" (GRaB score: >18); (ii) yellow light, corresponding to "medium impact" (GRaB score: 10–18); (iii) green light, corresponding to "low impact" (GRaB score: <10).

3. Results

3.1. *ALDFGs assessment in the portofino MPA*

A total of 91 ALDGFs was found covering an area of 350 m^2, of which 76 lines, 9 ropes, 5 nets and 1 trawl net, mostly on slightly inclined substrates (< 60°). More than half of ALDFGs (64%) were found "attached to the substrate" (Figs. 3B), and 76% were considered by volunteers as "difficult to remove". Twenty-seven ALDFGs presented entangled mobile fauna, 19 of which trapping a smaller number of organisms (≤5) (Fig. 2A). Only 3 out of 91 gears were considered clean (i.e., no or low epibiosis) or slightly colonized by sessile benthic organisms, while most of them were found moderately to highly colonized by both non-calcareous (60 items) (e.g., sponges, colonial ascidians, hydrozoans) and calcareous (79 items) (e.g., encrusting bryozoans and corallinaceans) species (Fig. 2A; Fig. S2).

Considering all taxa listed in the protocol, a total of 995 specimens were impacted by the ALDFGs. Overall, the red gorgonian *Paramuricea clavata* was the most affected taxon with 507 colonies interested by at least one ALDFG, followed by Corallinales (179), Bryozoa (141), *Axinella* spp. (105) and the red coral *Corallium rubrum* (52). Additionally, 10 *Eunicella cavolini,* 1 *E. singularis* and 1 *E. verrucosa* were found damaged by ALDFGs, while no *Savalia savaglia*, *Leptogorgia sarmentosa,* Ircinidae or *Pinna* spp. were found impacted (Fig. 2B). Almost all the affected organisms were found at Punta Chiappa (47%) and Punta del Faro (48%)

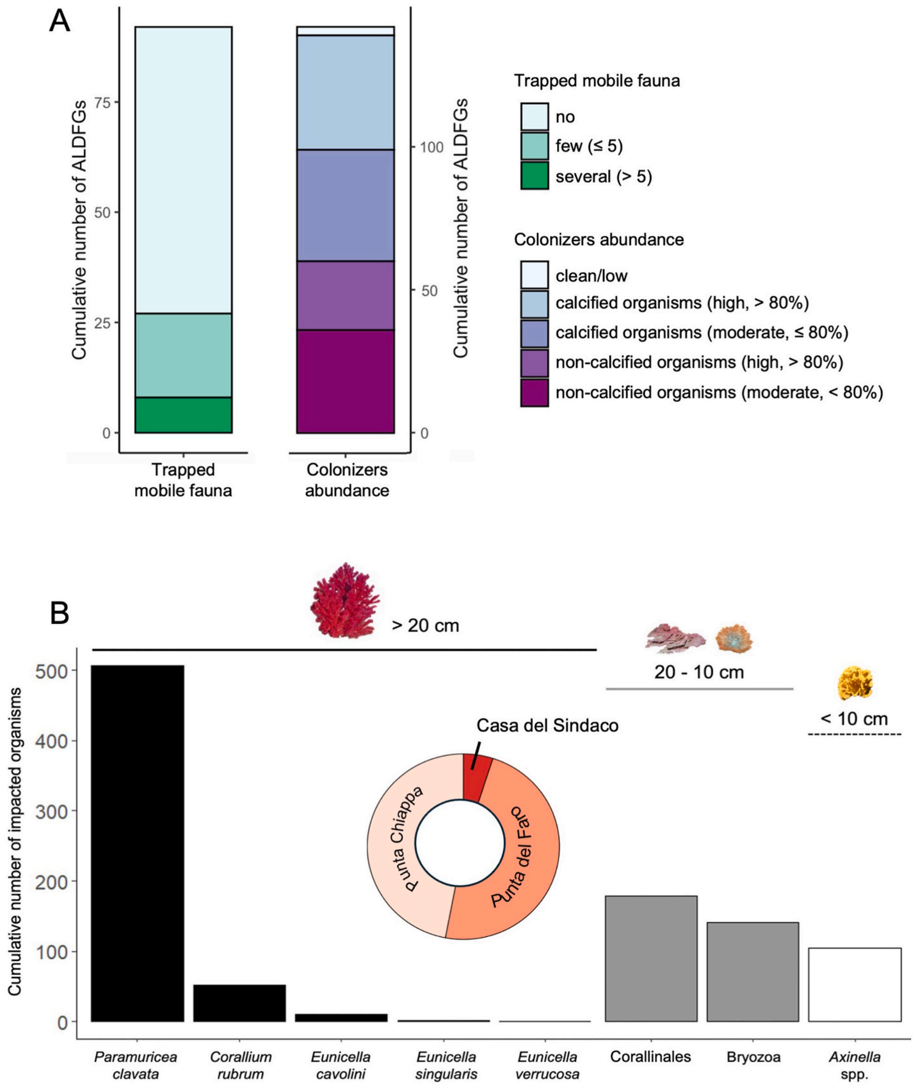

Fig. 2. (A) Stacked bar-plots showing the cumulative number of ALDFGs presenting trapped mobile fauna and epibiosis (i.e., colonizers), with the respective range of abundance. Please consider that for the creation of these plots each ALDFG could be included in one or more categories. (B) Bar-plot displaying the cumulative number of impacted organisms per taxon, and a donut plot indicating the percentage of impacted organisms per site. Please note that in the bar-plot, colours depict size ranges (<10 cm, 10–20 cm, >20 cm) based on the maximum height/extension of the considered taxa as reported in the literature (Canessa et al., 2022, 2023; Coma et al., 2006; Garrabou et al., 1998; Garrabou and Harmelin, 2002; Genta-Jouve et al., 2011; Linares et al., 2007, 2008; Rodriguez-Prieto et al., 2013; Rosso and Novosel, 2010; Vafidis, 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 2B); in fact, a significant difference in the abundance of organisms among sites was found (PERMANOVA, $p = 0.003$; Table 3A), with Punta Chiappa and Punta del Faro showing higher organism abundances compared to Casa del Sindaco (*a posteriori* pairwise tests, $p < 0.05$; Table S2A), as well as a higher number of ALDFGs (35 and 42, respectively).

A significant interaction of the factors site and type of damage was recorded by the two-way PERMANOVA ($p = 0.0021$; Table 3B). As a point of fact, Fig. 3 shows how, independently from the taxa abundance category, the prevalent damage recorded was entanglement of organisms to ALDFGs within all sites (*a posteriori* pairwise tests, $p < 0.05$; Tables S2B, C, D; Fig. S2 A-E), while records of broken or stripped organisms were related almost exclusively to *P. clavata* colonies (Fig. 3; Fig. S2 F). This taxon was also the one mostly contributing to the dissimilarities highlighted by the SIMPER analysis, followed by Corallinales, Bryozoa and *C. rubrum* depending on the site (Table S3).

3.2. GRaB index for removal assessment

The index produced reliable results when applied to the over 200 study cases. The cases with the greater estimated impact (Fig. 4A), thus falling into the "red category" of the traffic light representation, are represented by a trawl net and a gill net, displaying the higher scores of the GRaB index (21.8 and 18.7 out of 25, respectively). Both nets were found affecting over 50 habitat-forming corals (mainly *P. clavata* and *S. savaglia*) each, interesting highly rich coralligenous areas of Punta Manara, and in the case of the trawl net presenting a moderate coverage of calcified and not calcified organisms (Fig. 4A). Examples of moderate impact ("yellow category") include two fishing lines: (i) one with a GRaB index score of 17.5, which entangled a total of 34 *P. clavata,* 2 *C. rubrum* and 1 *E. cavolini* colonies on a slope hosting a dense aggregation of gorgonians; and (ii) another fishing line that, although entangling fewer organisms (10 red coral colonies), was located along a coralligenous overhang with several crowded areas of fragile *C. rubrum* colonies,

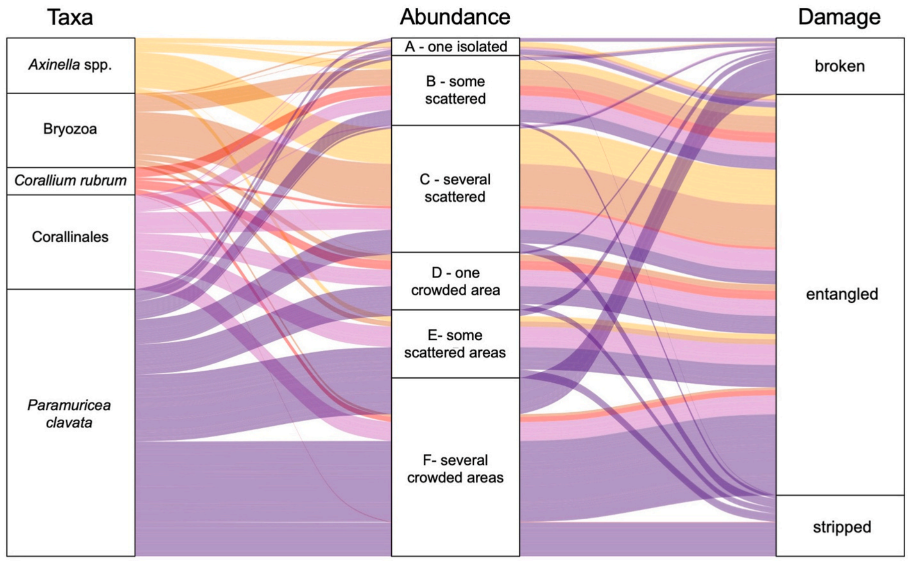

Fig. 3. Alluvial diagram of the taxa mostly impacted by ALDFGs, stratified by category of abundance and type of damage. Please note that the thickness of the lines is proportional to the number of individuals affected.

Table 3
Results of the PERMANOVA tests analysing (A) the variation of abundance of taxa impacted by ALDFGs among sites (3 levels, random), and (B) the variation in the number of organisms per taxa impacted by ALDFGs among sites (3 levels, random) and type of damage (3 levels, fixed). Significant p-values ($p < 0.05$) are given in bold. Df = Degrees of Freedom; SS = Sum of Square; MS = Mean Square; Pseudo-F = F value by permutation; P-perm = p-value; Unique perm = number of permutations.

A	Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
	Site (S)	2	10899	5449.4	6.2119	**0.0003**	9954
	Res	88	77198	877.25			
	Total	90	88097				
B	**Source**	**df**	**SS**	**MS**	**Pseudo-F**	**P(perm)**	**Unique perms**
	Site (S)	2	11745	5872.6	7.5604	**0.0001**	9953
	Damage (D)	2	46648	23324	11.509	**0.0332**	9073
	SxD	4	8999.5	2249.9	2.8965	**0.0021**	9941
	Res	258	2.00E+05	776.75			
	Total	266	2.90E+05				

resulting in a GRaB score of 15.65 (Fig. 4B). Finally, the low-impact cases ("green category") were exemplified by a fishing line (GRaB = 9.9) found entangling 4 *P. clavata* in a relatively poor area, and by a rope (GRaB = 6.45) located on a detritic bottom at the base of a coralligenous wall, affecting a couple of specimens of *Axinella* spp. and a bryozoan colony (Fig. 4C).

4. Discussion

The management and monitoring of ALDFGs in marine ecosystems has become a matter of increasing concern over the past years (Richardson et al., 2021, 2022). However, despite decades of recommendations and mitigation measures aimed at reducing ALDFG impacts (Hsiao and Chen, 2025; Richardson et al., 2021), the issue remains unresolved. Each year, hundreds of thousands of kilometres of nets and fishing lines, along with millions of pots and traps, are lost at sea; however, current estimates are largely derived from commercial fisheries, whereas data on gear loss from artisanal and recreational fisheries remain scarce (Richardson et al., 2022). In this context, we: (i) expanded the understanding of the impacts of small-scale fisheries within a well-established Italian MPA; (ii) identified the challenges faced by MPA managers in addressing these impacts; (iii) emphasized the potential of MCS for detecting and assessing ALDFGs through the application of a science-based standardized protocol; and (iv) developed a visual index, based on the protocol's data, to evaluate potential damage to benthic communities during hypothetical removal operations.

4.1. *ALDFGs assessment in the portofino MPA: a delicate balance between fishing exploitation and conservation efforts*

Despite a two-year fishing ban at Punta del Faro in 2016 (Administrative Resolution n.3 of January 20th, 2016), and systematic clean-up events since 2021, ALDFGs abundance in the Portofino MPA zone B remain considerable (Betti et al., 2020; Jacobsen et al., 2024). Of the 91 gears documented by RAN volunteers, most were at Punta del Faro and Punta Chiappa, the two extremities of the Portofino Promontory (Fig. 1), consistent with previous observations at Punta del Faro and Secca dell'Isuela, where Betti et al. (2020) located 40 and 30% of all records. These sites, exposed to strong currents and with high fish abundances (Cattaneo-Vietti et al., 2015; Doglioli et al., 2004), are known to experience intense fishing effort (Betti et al., 2020; Markantonatou et al., 2014), potentially explaining the higher ALDFG number found in these areas. Additionally, the level and type of epibiosis recorded, mainly represented by encrusting bryozoans and Corallinales, suggest abandonment occurred 5–11 months earlier (see Fig.7 in Enrichetti et al., 2021), consistent with the last clean-up. As a point of fact, the sites Punta del Faro and Punta Chiappa were already interested by previous removal events in 2021 and 2023 by RAN volunteers in collaboration with the Portofino MPA staff and the environmental organization World Wildlife Fund. In June 2021, a total of 60 kg of nets, ropes and lines were

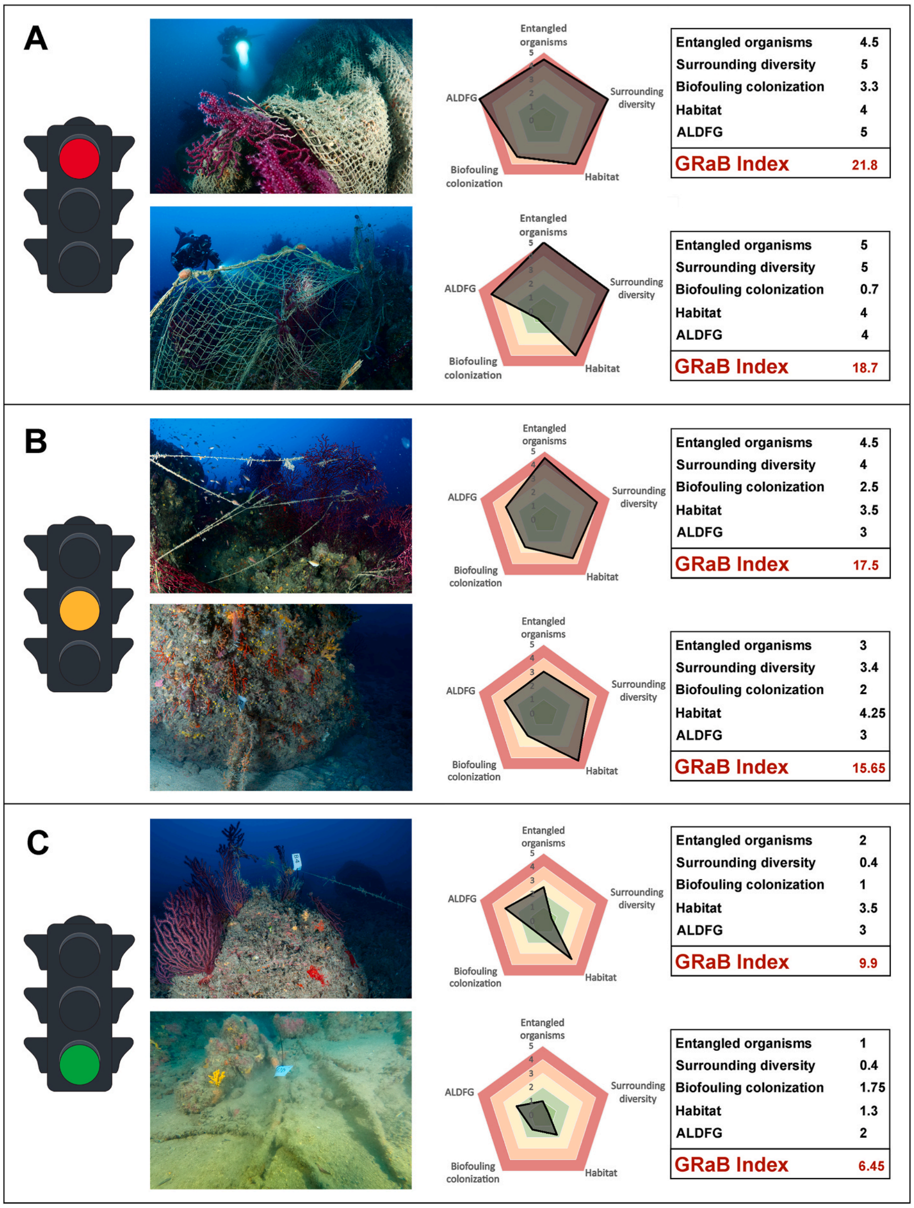

Fig. 4. Illustrative examples of the Gear Removal-Biological index (GRaB): (A) high ("red category" of the traffic light), (B) moderate ("yellow category" of the traffic light) and (C) low ("green category" of the traffic light) risk associated with the potential harming of biodiversity during ALDFG retrieval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

collected (https://reefalert.net/s/portofino/post/post/view?id=50), while in April 2023, up to 30 kg of fishing lines (around 1,500 m) were removed (https://reefalert.net/s/portofino/post/post/view?id=117). During the two campaigns, an average of 850€ per day was spent on clean-up actions, totalling € 11,000 for 13 days of activities.

Across the surveyed area of 350 m^2, 91 ALDFGs (0.26 ALDFG/m^2) damaged 995 organisms in coralligenous assemblages. ROV surveys from 2012 to 2016 (4,905 m^2, 29–106 m depth) documented 480 ALDFGs (0.096 ALDFG/m^2) (Enrichetti et al., 2020, 2023), while Jacobsen et al. (2024) found 120 lines affecting 72 organisms over 720 m^2 (0.16 ALDFG/m^2) at 35 and 50 m depths. The lower impact observed by Jacobsen et al. (2024) in a similar depth range likely reflects different study aims, with the ALDFG assessment being a complementary consideration, while temporal trends suggest a growing fishing pressure. Despite awareness campaigns (i.e., leaflets and training courses) targeting fishers were led by the MPA staff, stricter regulations (e.g., open discussions with fishery actors, the use of sustainable gears, long-lines ban) should be considered by the management bodies, leaving ALDFGs removal as the very last option.

In line with previous assessments in the area (Betti et al., 2020; Jacobsen et al., 2024; Valisano et al., 2019) and other Mediterranean locations (Angiolillo et al., 2015; Chimienti et al., 2023; Consoli et al., 2018, 2019; Enrichetti et al., 2019; Kipson et al., 2015), with over 500 colonies affected, the red gorgonian *Paramuricea clavata* was the most impacted species. This key species, dominant in coralligenous habitats (Cerrano et al., 2005; Jacobsen et al., 2024; Palma et al., 2018), emerges from the substrate of about 34 cm (Betti et al., 2020), resulting highly prone to entanglement (Angiolillo and Fortibuoni, 2020). Gear damage was proven to reduce its thermal resistance, feeding capacity, and recovery potential, mining population resilience (Bavestrello et al., 1998; Corinaldesi et al., 2022; Vezzulli et al., 2013). Additionally, as previously observed in the area (Azzola et al., 2021; Enrichetti et al., 2020; Jacobsen et al., 2024; Valisano et al., 2019), other coralligenous taxa, including *Corallium rubrum* and other gorgonian species, *Axinella* sponges, bryozoans and Corallinales, were also found impacted, ultimately leading to habitat fragmentation and community structure alteration (Cerrano and Bavestrello, 2008; Ponti et al., 2014; Valisano et al., 2019).

Alongside fishing impacts, recurring mass mortalities and mucilage outbreaks are degrading coralligenous habitats at basin scale (Garrabou et al., 2022b; Montalbetti et al., 2023), reducing habitat complexity and ecosystem services (Gómez-Gras et al., 2021). Quantifying the related natural capital loss is challenging but crucial to fully understand the economic consequences (Döhring et al., 2023). In the case of the Portofino MPA, considering an average ALDFG removal cost (850 €/day) and the natural capital of the MPA estimated for 10 em€/m^2 (Paoli et al., 2018), the current fishing fees (https://www.portofinoamp.it) remain highly insufficient to offset the caused damages.

4.2. *Marine citizen science: a diamond in the rough*

In recent years, the rising number of recreational and technical divers passionate about marine conservation has fuelled a strong growth in MCS initiatives (Cerrano et al., 2017; Forrest et al., 2023; Lucrezi et al., 2022; Turicchia et al., 2021), reinforcing the link between the diving community and researchers (Kawabe et al., 2022). In this context, the RAN *Conservation Diver* program offers to volunteers the unique opportunity to collaborate with researchers in collecting high-quality data (Coppari et al., 2024; Figuerola-Ferrando et al., 2024; Lucrezi and Cilliers, 2023). Operating within an MPA, it supports systematic monitoring, data sharing with local management, and collaboration among citizens, researchers, stakeholders, and policymakers (Coppari et al., 2024; Intonti et al., 2024), aligning with the aims of the UN Ocean Decade and of the Sustainable Development Goal 14 (*Life Below Water*) of the 2030 Agenda (von Schuckmann et al., 2020).

Other initiatives, led by researchers and divers, are currently active at European and global scales (e.g., Coral Soul, Norwegian Diving Association, Fish&Click, Ghost Diving, Ghostnet by Sea Shepherd, MARsCI project) (https://www.ghostdiving.org; https://www.coralsoul.org/; https://www.seashepherdglobal.org/our-campaigns/ghostnet-campaign/; Mehrotra et al., 2024; Morfin et al., 2025; Thorbjørnsen et al., 2023). With just a few exceptions, most of these initiatives are primarily focused on ALDFGs location and removal. Conversely, the *Conservation Diver* project incorporates a strong didactic and monitoring component, not only regarding ALDFGs but also of the potentially impacted organisms and the surrounding biodiversity. As a point of fact, volunteers follow an intense training program composed of: (i) theoretical sessions, during which they learn how to apply the protocol and how to identify the species characterizing the habitat of interest; and (ii) one or more dives, in which volunteers exercise in the protocol application. While other initiatives consider an intensive theoretical component as less appealing for potential volunteers (e.g., Mehrotra et al., 2024), in the *Conservation Diver* program it is highly developed and always conducted by expert marine biologists (Coppari et al., 2024), thus ensuring the collection of more reliable and accurate data (Schläppy et al., 2017).

4.3. *The GRaB index: strength points, limitations, and future directions*

In parallel with the RAN protocol, we introduced a simple, field-ready index. Previous indexes considering ALDFGs-related impacts on the Mediterranean benthic component include the GRI and the GRI+ indexes (Jimenez and Resaikos, 2025; Ruitton et al., 2020). These indexes show similarities and substantial differences with the here proposed GRaB index. All indexes consider the type of habitat, level of colonization of the gear, engagement of the seafloor and damage/presence of habitat formers; however, even though the entire environmental component account for ~64% of the total GRI/GRI+ score variation, the damage to habitat formers or their presence nearby the ALDFG account only for a 5.5%. By contrast, the GRaB index estimates the potential damage caused by removal operations to both organisms entangled in the gear and the surrounding benthic community, reaching up to a 40% of the total score. Although large, sessile taxa are among the organisms most affected by ALDFGs (Angiolillo and Fortibuoni, 2020; Duncan et al., 2023), their role in ghost-fishing impact assessments remains underrepresented (Do and Armstrong, 2023; Higueruelo et al., 2023). Prioritizing these taxa as key indicators is, therefore, a central strength of the GRaB index.

Additional strengths include ease of use, automated calculations, and an immediate, easily interpretable graphical output. Mobilizing citizen participation in ALDFGs detection and recovery will increase survey effort, the number of gear items located and safely removed, and the volume of data available to assess coralligenous assemblages and other vulnerable habitats (Di Camillo et al., 2023; Kelly et al., 2020). When a GRaB score falls in the medium or high-impact categories, however, a marine biologist must be involved in planning the removal (Azzola et al., 2025). In these cases, targeted *in situ* inspections or review of photo/-video documentation are needed to define the best practices. For example, where an ALDFG covers a large area and affects numerous organisms (see Fig. 4A), the gear should be sectioned into manageable pieces for safer handling and all entangled organisms carefully released (Marine Management Organization, 2018). When gear hosts species of high ecological value (Fig. 5), removal should be planned together with transplanting and restoration actions (Danovaro et al., 2025). This integrated approach is already adopted by the *Conservation Divers* program and similar initiatives in the Mediterranean and elsewhere (e.g., Coral Soul; Rescue a Reef) (Coppari et al., 2024; Disney et al., 2017; Hesley et al., 2017; Palacios-Miñambres et al., 2024).

Although the GRaB index was developed for the Mediterranean, particularly for coralligenous habitats, ALDFGs represent a global threat. The implementation of international, collaborative network of monitoring, control and surveillance initiatives could help in better adapting both the protocol and the visualization tool to other habitats/species impacted by fishing gears. Producing cross-habitat, multi-species guidelines for ALDFGs monitoring and removal would support local stakeholders in conservation and restoration efforts, in line with the 2030 Agenda and the recently approved Nature Restoration Law

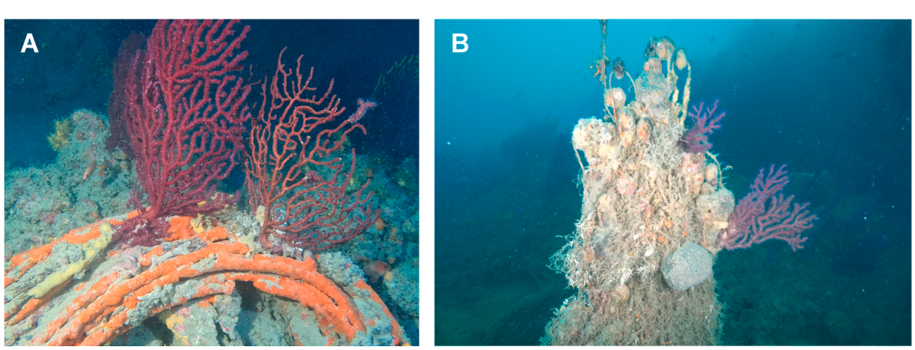

Fig. 5. Examples of ALFDGs hosting organisms of high ecological value: (A) a metallic wire colonized by colonies of *Paramuricea clavata* and various encrusting sponges; (b) a gill net, partially floating, presenting colonies of *P. clavata*, the sponge *Sarcotragus foetidus* and other keratose sponges.

(Ferreira et al., 2021; Fritz et al., 2019).

Besides the robustness of the GRaB index, two main limitations can be identified. Firstly, the index value may vary with the time interval between the ALDGF assessment and the actual clean-up operation. This variability may arise from the type of gear involved, progressive biological colonization of the gear, and/or the entanglement of additional organisms. For this reason, a second assessment conducted closer to the removal operation is recommended. Secondly, a potential sampling bias can derive from the limited and inconsistent use of technical diving throughout the basin, which, currently, confines survey efforts primarily to shallow sites. To scale up the protocol and the GRaB index, it will extend the call to other Mediterranean areas and engage a broader network of divers and diving centres, thereby expanding citizen-supported underwater data collection and enabling crowdsourced refinement of the protocol.

4.4. Implications for the management of ALDFGs

Although the proposed protocol and index have proven effective in monitoring ALDFGs, assessing their impact, and estimating the ecological outcomes of their removal, considerable future efforts will be needed to mitigate professional and artisanal fishing in highly vulnerable habitats, especially within MPAs boundaries (Higueruelo et al., 2023; Venturini et al., 2017, 2019). As repeatedly suggested in the existing literature (e.g., Betti et al., 2020; Higueruelo et al., 2023; Macfadyen et al., 2009), there is a growing list of recommendations that should be enforced to fishers as a standard, such as a mandatory identification label in fishing gears to trace ownership, the use of sustainable bio-degradable fishing gears, or banning the use of the most impacting ALDFGs. In line with these new standards, a strengthening of surveillance along with more severe sanctions/penalties should be considered to prevent illegal fishing and mitigate fishing impacts.

Additionally, urgent implementation of educational programs is needed to foster a deeper environmental awareness among fishers (Mistri et al., 2024; Odhiambo et al., 2025), by encouraging a greater respect for marine ecosystems and promoting the understanding that certain habitats must be preserved, as they serve as vital reservoirs for future fisheries. Rewarding fishers through certifications or sustainability badges (www.fao.org) should be limited to those who adhere to environmentally responsible practices. It will be essential to inform end-consumers about the differences between sustainable and unsustainable seafood, highlighting how their choices play a key role in protecting marine habitats and ensuring the long-term future of fisheries.

CRediT authorship contribution statement

Camilla Roveta: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Torcuato Pulido Mantas:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Simone Berardone:** Writing – review & editing, Formal analysis, Data curation. **Federico Betti:** Writing – review & editing, Methodology. **Martina Coppari:** Writing – original draft. **Valentina Cappanera:** Writing – review & editing, Supervision. **Cristina Gioia Di Camillo:** Writing – original draft, Visualization, Methodology, Data curation. **Francesco Enrichetti:** Writing – review & editing, Methodology. **Lorenzo Merotto:** Writing – review & editing, Supervision. **Giorgia Sanna:** Formal analysis, Data curation. **Alessia Bacchi:** Writing – review & editing, Funding acquisition. **Carlo Cerrano:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Data statement

All data are available throughout the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors (as non-native English speakers) used ChatGPT, an AI language model developed by OpenAI, to improve the clarity of the manuscript's language.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.108072.

Data availability

Data will be made available on request.

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