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Marine Ecosystem Restoring by High-Complexity Artificial Reefs (HCAR)

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Abstract The establishment of a High-Complexity Artificial Reef (HCAR) along the Catalan coast in Spain prompted an investigation into the ecological rehabilitation of coastal ecosystems in the Western Mediterranean region. This study monitored marine succession by examining fish assemblage descriptors across seasons. Employing scuba diver video image analysis, we documented the emergence and evolution of HCAR structures from October to July. This analysis facilitated species identification, fish abundance quantification, and the assessment of the Shannon-Weaver Diversity Index at 5-second video intervals. The observed species primarily belonged to characteristic taxa of the western Mediterranean, with *Pomadacys incisus* (45.7%), *Cromis chromis* (26.9%), and *Diplodus vulgaris* (18.8%) among the frequently encountered species. Both fish abundance and the Shannon-Weaver Diversity Index exhibited an increasing trend over time, suggesting progressive ecosystem succession, notably during the spring-summer period. These findings highlight the potential of novel artificial reef designs to foster fish population growth and enhance biodiversity. However, to comprehensively assess the long-term stability and potential of HCAR, extended monitoring periods are imperative. In conclusion, this study underscores the positive influence of high-complexity artificial reefs on marine succession. It emphasizes the necessity for prolonged monitoring to elucidate their sustained impact on coastal ecosystems.

Keywords Video-image analysis; Fish community; High-complexity artificial reefs; *Pomadasys incisus*; *Chromis chromis*; *Diplodus vulgaris*

Marine ecosystems are crucial sources of resources and services for humans, yet they face severe degradation due to human-induced factors such as overfishing and coastal development. This human encroachment has predominantly occurred along marine coasts, marking the forefront of extensive anthropogenic influence. To counteract these declines, there has been a heightened focus on marine restoration endeavours in recent decades, motivated by concerns encompassing social, economic, and governmental management, aiming to reinstate and sustain healthy marine ecosystems (Pitcher and Seaman, 2000; Claudet and Pelletier, 2004; Carpenter et al., 2006; Montoya et al., 2006).

Shallow coastal areas stand as pivotal environments necessitating restoration efforts, essential for rectifying disturbances resulting from human activities (Bayle-Sempere et al., 2001; Charbonnel et al., 2002; Moreno, 2002; Seaman, 2007). Understanding seasonal variations in fish abundance is imperative for effective environmental monitoring (Willis et al., 2000). However, fish stocks exhibit variability across temporal and spatial scales due to animals' behavioural responses to habitat alterations and natural succession. Accurate evaluation of these fluctuations is critical for management strategies, such as establishing Marine Protected Areas (MPAs) and deploying Artificial Reef Structures (Willis et al., 2000; Harmelin-Vivien et al., 2008; Condal et al., 2012; 2020).

Recent decades have witnessed substantial efforts in deploying innovative Artificial Reefs (ARs) for biological and habitat restoration across diverse marine environments globally (Relini et al., 2002a; 2002b; Jensen, 2002; Claudet and Pelletier, 2004; Seaman, 2007; Koeck et al., 2011; 2014; Layman and Allgeier, 2020; Ramm et al., 2021; Vivier et al., 2021). Utilization of underwater video cameras in marine science has facilitated visual censuses, enabling the assessment of species' populations and overall biodiversity at varying temporal and spatial scales. Additionally, digital imaging systems play a crucial role in faunal exploration and monitoring despite encountering biological hazards (Zenetos et al., 2010; Condal et al., 2012; 2020; Nalmpanti et al., 2023).

One of the most promising tools for marine restoration is the concept of High-Complexity Artificial Reefs (HCARs), intended to emulate the intricate nature of natural reefs, providing diverse habitats and shelter for a wide array of marine species (Willis et al., 2000; Harmelin-Vivien et al., 2008; Condal et al., 2012; 2020). While HCARs hold the potential to enhance species' habitat, serving as refuges from fishing pressures, and augmenting targeted species' biomass, challenges such as potential overfishing, construction and maintenance costs, and susceptibility to climate change and ocean acidification necessitate careful consideration (Willis et al., 2000; Harmelin-Vivien et al., 2008; Condal et al., 2012; 2020; Hylkema et al., 2020).

This study represents an unprecedented attempt at seasonal fish community monitoring within HCARs on the Mediterranean seafloor. We conducted seasonal samplings in an HCAR within a western Mediterranean marine reserve to delineate ecosystem succession and observe new fish species colonization, potentially influencing estimated biodiversity levels. Integrating research on HCARs, seasonal fish abundances, and ecosystem succession offers insights into the role of these artificial structures in fostering marine restoration and biodiversity conservation (Le Diréach et al., 2015). This knowledge significantly contributes to the effective management of marine protected areas and the sustainable deployment of AR structures. In conclusion, while HCARs hold promise as tools for restoring marine ecosystems due to their ability to mimic natural reef complexity and provide diverse habitats, meticulous attention to their limitations and long-term effectiveness is imperative. Continuous research and monitoring efforts are indispensable to fully unleash the potential of HCARs and ensure the preservation and restoration of marine ecosystems for future generations.

1 Results and Analysis

A total of 960 seconds of video footage (equivalent to 16 minutes) underwent thorough analysis (Table 1), with a notable majority (98%, amounting to 944 seconds) recorded under optimal visibility conditions. However, it is essential to note the absence of winter video imagery due to adverse water visibility conditions. Specific time intervals were meticulously identified to facilitate analytical precision across each season: autumn (168 seconds), spring (415 seconds), and summer (377 seconds). Within the scrutinized video footage, 2684 fish images were meticulously classified at the species level. Regrettably, certain distant images posed challenges for species classification, leading to their exclusion from the analysis. The catalogued fish species encompassed 19 distinct types, spanning 12 different families, including *Congridae*, *Gobiidae*, *Haemulidae*, *Labridae*, *Molidae*, *Mullidae*, *Pomacentridae*, *Sciaenidae*, *Scorpaenidae*, *Serranidae*, *Sparidae*, and *Trachinnidae* (Table 2). Alongside the fish species, other intriguing or invasive species were observed during the study. For instance, the persistent presence of *Caulerpa racemosa* seabed throughout all sampling seasons and other filamentous algae common in polluted seawater was noted a year after HCAR depletion.

The total count of fish per species, along with their corresponding occurrence percentages within the entire video-frame set (Table 2). Among the identified fish, three species – Bastard grunt (*Pomadasys incisus* Bowdich, 1825), Damselfish (*Chromis chromis* Linnaeus, 1758), and Two-banded seabream (*Diplodus Vulgaris* Geoffroy Saint-Hilaire, 1817) – comprised a substantial 91.6% of all identified fish species. Notably, these species occasionally formed large schools, some instances comprising 20 or more individuals. However, the remaining species were less prevalent in the video frames. Most species exhibited variations in occurrence patterns across the seasons (Figure 1D; Figure 1E; Figure 1F), showing a discernible temporal trend.

Table 1 Some video-sample examples from the area of study

Month	Time	Area sampled	Link
June	12’16”	Sandy bottom	https://youtu.be/4wXriV2x47s
		Central core HCAR	-
		Inside central core HCAR	-
		Individual HCAR	-
		Water column	-
		Sandy bottom	https://youtu.be/VYUEFr132yM
	22”	Sandy bottom	https://youtu.be/4dLutScGRcc
	27”	Sandy bottom	https://youtu.be/Lo--qjNJ1n0
	13”	Sampling technique	https://youtu.be/FGtBZDo-h6g
	20”	Individual HCAR	https://youtu.be/zGQGVstxUhM
	21”	Inside indiv. HCAR	https://youtu.be/SpQVHUwfw5w
	14”	Individual AR	https://youtu.be/ekSr6FIVPtA
	10”	Inside indiv. HCAR	https://youtu.be/bpr4rvNuNbc
	45”	Individual HCAR and inside	https://youtu.be/7CBeKppocl4
	15”	Sandy bottom and indiv. HCAR	https://youtu.be/laOagxGYBhI
August	3”	Sandy bottom	https://youtu.be/lfvjQKQzg8k
	5”	Inside indiv. HCAR	https://youtu.be/oZj3e26jWgw
	1’09”	Inside indiv. HCAR	https://youtu.be/dtvOKUxgFeY
	27”	Central core HCAR and	https://youtu.be/E0M4Lc2nK4E
		Inside central core HCAR	-
	11”	Individual HCAR	https://youtu.be/J8RIABV6vIE
	42”	Inside central core HCAR	https://youtu.be/M9hkPp5qDc8
	1’12”	Central core HCAR and	https://youtu.be/mjXhBQjqUxg
		Inside central core HCAR	-
	54”	Individual HCAR	https://youtu.be/ibIzrVsS2fY

Note: Items are month, duration of video samples, area of video recorded and online link for visualization

Table 2 List of species observed, total number of fish observed and percentage of occurrence, trophic level, mean trophic level and mean trophic level standardized to the video-transects analysed

Common name	Scientific name	%	TL
Bastard grunt	*Pomadasys incisus*	45.83	3.8
Damselfish	*Chromis chromis*	26.94	3.38
Two-banded seabream	*Diplodus vulgaris*	18.85	3.34
Red mullet	*Mullus barbatus*	3.95	3.24
White seabream	*Diplodus sargus*	2.16	3.24
Annular seabream	*Diplodus annularis*	0.63	3.21
Comber	*Serranus cabrilla*	0.48	3.68
Bogue	*Boops boops*	0.22	3.11
Striped goby	*Gobius vittatus*	0.19	2.94
Saddled seabream	*Oblada melanura*	0.19	3.38
Brown meagre	*Sciaena umbra*	0.15	3.83
Rainbow wrasse	*Coris julis*	0.07	3.24
Red scorpionfish	*Scorpaena scrofa*	0.07	3.95
Ocean sunfish	*Mola mola*	0.07	3.28
Gilthead seabream	*Sparus auratus*	0.04	3.39
Common dentex	*Dentex dentex*	0.04	4.5
European conger	*Conger conger*	0.04	4.26
Small red scorpionfish	*Scorpaena notata*	0.04	3.44
Guinean weever	*Trachinus armatus*	0.04	3.66
Total number of fish visualizations		2684	
Mean trophic level		3.52	
Mean trophic level standarized		3.43	

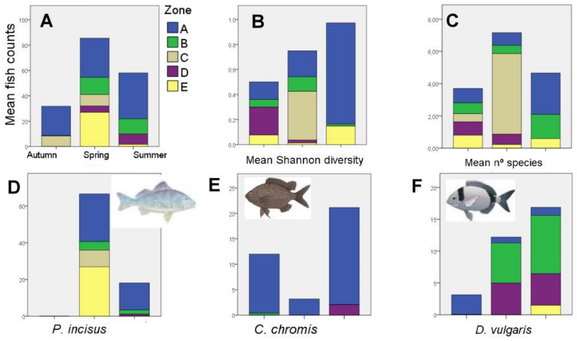

Figure 1 Mean number of: fish identified, Shannon-Weaver-weaver Diversity Index, species identified, *Pomadasys incisus, Diplodus vulgaris* and *Chromis chromis*

Note: Seasons and zones are: autumn, spring, summer. A: Central core HCAR; B: Inside central core HCAR; C: Individual HCAR; D: Inside individual HCAR; E: Sandy bottom with *Caulerpa racemosa*

Comprehensive data on mean fish counts, species richness, and Shannon-Weaver Diversity Index (H') per video interval categorized by zone (representing different complexity levels) and year for autumn, spring, and summer seasons (Table 3). Each season includes specific sampling data corresponding to substrata types labelled as A, B, C, D, and E assumed to represent various habitats, ecological niches or AR configurations. This complexity levels are; A) Central core HCAR, B) Interior of the central core HCAR, C) Individual HCAR, D) Interior of individual HCAR, and E) Sandy bottom hosting *C. racemosa* (Figure 2A; Figure 2B; Figure 2C; Figure 2D).

In autumn, zone A displayed the highest mean fish count of 23.0 (sdv. 13.7) per image, indicating relatively higher fish abundance compared to other zones (B, C, D, and E). Zones B and C exhibited lower fish counts, with mean values of 0.5 (sdv. 0.6) and 8.3 (sdv. 0.0) fish per video interval, respectively. Species richness, depicted by the mean number of species per image, remained relatively low across all zones in autumn, ranging from 0.5 to 0.9 species. Zone A exhibited the highest mean species count (0.9), followed by areas C and D. The Shannon-Weaver Diversity Index (H') in autumn was generally low across all zones, indicating limited fish community diversity after HCAR deployment. Zone A demonstrated the highest diversity with a mean H' value of 0.14 (sdv. 0.1), while the other areas displayed lower values ranging from 0.06 to 0.22.

Table 3 Mean number of fish identified, mean number of species, and mean Shannon-Weaver-weaver Diversity Index per 5 seconds of video from 3 sampled seasons

Season	Zone	Total	sdv	Nº sp	sdv	H'	sdv
Autumn	A	23.0	13.7	0.9	0.9	0.14	0.1
	B	0.5	0.6	0.7	0.1	0.06	0.0
	C	8.3	0.0	0.5	0.0	0.00	0.0
	D	0.0	0.0	0.8	0.0	0.22	0.0
	E	0.0	0.0	0.8	0.0	0.08	0.0
Spring	A	30.9	26.1	0.8	0.7	0.21	0.2
	B	13.6	17.4	0.5	0.4	0.12	0.1
	C	9.0	0.0	5.0	0.0	0.39	0.0
	D	5.0	1.7	0.6	0.3	0.02	0.0
	E	27.0	0.0	0.2	0.0	0.01	0.0
Summer	A	36.1	28.4	2.6	2.2	0.81	0.9
	B	11.9	5.9	1.5	2.3	0.02	0.0
	D	8.2	1.6	0.0	0.0	0.00	0.0
	E	1.8	3.6	0.6	0.4	0.15	0.1

Note: A: Central core HCAR; B: Inside central core HCAR; C: Individual HCAR; D: Inside individual HCAR; E: Sandy bottom with *Caulerpa racemosa*

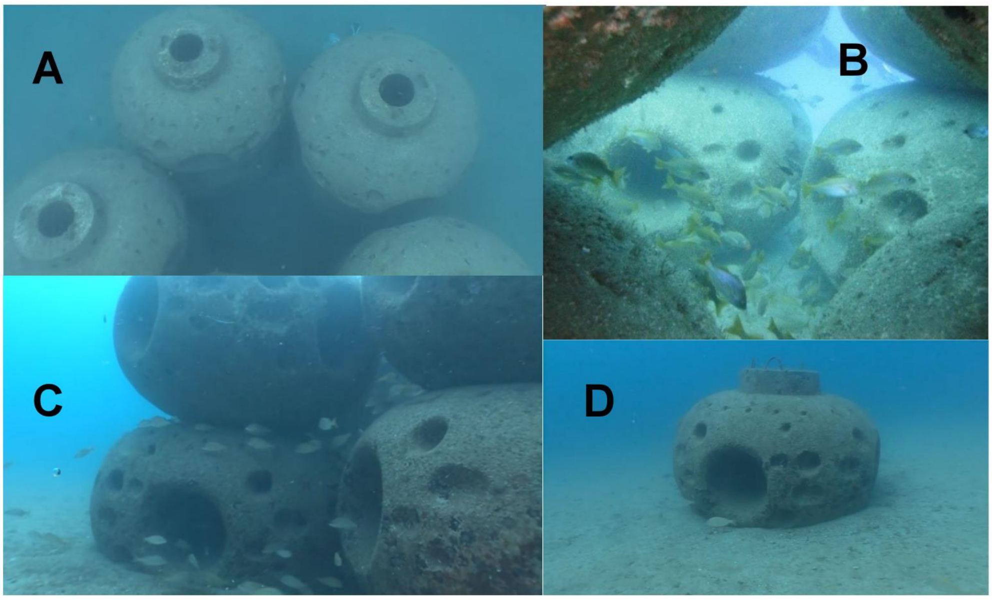

Figure 2 Structure of Geodes, that form the HCAR
Note: Central core area (A, C); Inside central core area (B); Individual HCAR (D)

In spring, zone A retained the highest mean fish count of 30.9 (sdv. 26.1) fish per image interval, with zones B, C, D, and E also showing increased counts compared to autumn. Species richness in spring and summer exhibited an increase, with mean values ranging from 0.2 to 5.0 species per image interval (Figure 1C). Zone C notably displayed the highest mean species count (5), indicating a more diverse fish community. Both spring and summer demonstrated improved Shannon-Weaver Diversity Indexes (H'), with zone C showing the highest mean diversity (H' value of 0.39, sdv. 0), indicating a more evenly distributed and diverse fish community. Other zones maintained moderate diversity levels, ranging from 0.01 to 0.21. Similar fish assemblage patterns were observed in summer across the zones, consistent with the findings for the entire year.

Seasonal variations in important fish assemblage descriptors and species counts for the top three abundant species (*P. incisus*, *C. chromis*, and *D. vulgaris*) (Figure 1). The analysis revealed fluctuating values of image biodiversity (H') throughout the study period, ranging from a maximum of 0.45 in June to a minimum of 0.06 in March. Seasonal variation in H' was confirmed by plotting values over the seasons, with higher diversity in May and June and lower in March. Autumn reported the lowest mean H' values, while higher means occurred in both spring and summer (Figure 1B). There were marked differences in the presence and abundance of fish species between camera transects (zones) in the study area (Table 3).

The seasonal sampling revealed notable variations in biodiversity and species abundance. In relation to autumn showcased a higher prevalence of species like *C. chromis*, contributing to an increased Shannon-Weaver Diversity Index. Conversely, spring exhibited a higher abundance of *P. incisus*. During summer, there was an elevated number of *C. chromis* and *D. vulgaris* (Figure 1D; Figure 1E; Figure 1F). Finally, unlucky due to sampling conditions data from summer in substrata type C (zone) was not able to be collected, and comparisons resulted a bit uncomplete. The seasonal sampling efforts revealed notable fluctuations in both biodiversity and species abundance (Figure 1, Table 3).

2 Discussion

This study introduces a novel observational protocol aimed at assessing succession changes in a reef fish community post-establishment of High-Complexity structures forming an Artificial Reef (HCAR). This investigation represents a challenging yet valuable approach to comprehending the ecological transition and succession dynamics within the newly formed reef ecosystem. The findings reveal significant temporal variations in various fish assemblage descriptors, highlighting the potential of HCAR structures in facilitating marine ecosystem restoration and mitigating environmental and fisheries-related impacts (Paxton et al., 2020).

Despite the innovative nature of the protocol, acknowledging potential inherent biases is imperative. Nonetheless, the protocol facilitates meaningful spatial and temporal comparisons, providing valuable insights. Noteworthy advantages of the new protocol include its ability to store video samples across different time windows for comprehensive analyses. However, it is crucial to recognize drawbacks such as sampling costs and potential inaccuracies in fish counts. The study successfully detected numerous species in the HCAR at Colls i Miralpeix, Costes del Garraf Marine Protected Area. Still, it is essential to note the potential incompleteness of the fish faunal list due to preliminary observations and the recent deployment of Artificial Reefs (ARs) in the marine park. Despite a thorough analysis of images, certain crypto-benthic species may have been inadvertently overlooked (Condal et al., 2012). To bolster primary conclusions, it is recommended to conduct more rigorous statistical analyses and intensify sampling efforts. This approach will establish a stronger foundation for interpreting observed ecological transitions and succession dynamics within the reef fish community influenced by HCAR deployment (Paxton et al., 2020).

Regarding the acquired list of fish species, their relative abundances, and trophic levels, the samples exhibit a dominance of species with relatively low trophic levels, potentially impacting the ecosystem structure and energy flow. Although higher trophic level species are present in smaller proportions, noteworthy examples such as the Common dentex (*Dentex dentex* Linnaeus, 1758) and European conger (*Conger conger* Linnaeus, 1758) display the highest trophic levels at 4.5 and 4.26, respectively, playing a crucial role in regulating lower trophic levels. On the other hand, it is worth noting that certain species, such as Gilthead seabream (*Sparus auratus* Linnaeus, 1758), Red scorpionfish (*Scorpaena scrofa* Linnaeus, 1758), and Ocean sunfish (*Mola mola* Linnaeus, 1758), exhibit low occurrence, suggesting their rarity or infrequency during the sampling period.

Variability in species counts during HCAR's seasonal and successional evolution correlates with changes in environmental conditions (e.g., water temperature, light availability, nutrient levels). These factors significantly shape marine ecosystem dynamics, influencing species distribution and behaviour. The AR established in the Catalan Sea fosters a conducive habitat for diverse marine organisms, facilitating different species' thriving during specific seasons. Reported seasonal population fluctuations link to individual species behaviour changes following AR deployment's ecosystem succession and evolution (Condal et al., 2012; 2020). Numerous faunistic observations contributed to compiling a comprehensive list of resident marine species, resembling other Western Mediterranean areas, notably *P. incisus* dominance, aligning with similar studies (Doumpas et al., 2020). Remarkably, *Haemulidae* and *Sparidae* species prevalence links to the AR presence, confirming increased *Sparidae* in AR environments from ecological and ethological perspectives (Charbonnel et al., 2002; Relini, 2002b). In the intricate web of the artificial reef ecosystem, *P. incisus*, *C. chromis*, and *D. vulgaris* emerge as pivotal players. *P. incisus* assumes a crucial predatory role, regulating the population sizes of smaller fish species and crustaceans, thereby maintaining ecological balance. *C. chromis* fulfills multiple ecological functions as a primary consumer, grazing on plankton and algae to control algal growth and contribute to nutrient cycling. Additionally, it serves as prey for larger predators, facilitating energy transfer within the food web. *D. vulgaris* acts as an omnivorous feeder, consuming small crustaceans, molluscs, and algae, thereby contributing to nutrient cycling and energy transfer within the ecosystem. These species interact with their environment by influencing prey abundance, modifying habitat structure through grazing behaviours, and participating in energy transfer dynamics. Collectively, their interactions shape the structure and functioning of HCAR, highlighting their importance in maintaining biodiversity and ecosystem health.

Zone A (Central core HCAR) consistently holds the highest mean fish count, indicating its significance in fish abundance, while zone C (Individual HCAR) displays higher species diversity and evenness. Differences in metrics suggest variability due to ecological factors, seasonal changes, or spatial heterogeneity. The ARs significantly influences *Sparidae* distribution (e.g., *D. vulgaris*) and other species (e.g., *C. chromis*), impacting resulting community composition, as observed in Fish counts and Shannon-Weaver Diversity Index. Differences across zones (camera transects) sometimes suggest variations due to the bidirectional movement of individuals, migration, and recruitment influencing fish biomass in coastal areas. Ecosystem succession and complexity primarily affect fish assemblage descriptors also (Thurner et al., 2018). Finally, acknowledging potential data errors is important, introducing uncertainty that might affect dataset robustness. Employing a deliberate approach to address this issue, viewing errors as potential aids in more robust comparisons is crucial. Assuming uniform error distribution across all dataset samples, including variables like season and zone allows more reliable comparisons even in the presence of data errors (Thurner et al., 2018).

Artificial barriers often positively impact fish diversity and abundance (Watson et al., 2005). Previous Western Mediterranean studies highlight similar effects, suggesting a general dynamic (Bayle-Sempere et al., 2001; Charbonnel et al., 2002; Relini et al., 2002a). Habitat heterogeneity, often facilitated by these structures, increases fish species numbers and interaction complexity, enhancing community stability against perturbations (Montoya et al., 2006; Carpenter et al., 2006; Thurner et al., 2018). Colonization by sedentary animals and plants relying on hard substrates for life cycles enhances juvenile recruitment across fish and crustacean decapod species (Pitcher and Seaman, 2000; Jensen, 2002; Moreno, 2002). This colonization process crucially establishes benthic ecosystems, connecting benthos and plankton. Examining ARs' impact on animal behaviour is essential. Fish schools' positioning based on reef orientation optimizes swimming efficiency, minimizing drag during strong currents episodes, particularly in *D. vulgaris* and other species near ARs (Bayle-Sempere et al., 2001; Condal et al., 2012; 2020). Cleaning stations formed by small *Labridae* species further drive fish aggregation. Researchers (Charbonnel et al., 2002) suggest fish are drawn to reefs to enhance feeding efficiency, with energy transfer to fish through decapods, amphipods, and juvenile fish concentrated in these structures (Relini et al., 2002a).

Restoration structures like ARs attract also fish populations significantly. However, outcomes are influenced by spatial and temporal variability, necessitating nuanced differentiation between fish density and habitat capacity increases. As noted by Polivka (2022), while these structures may elevate fish densities, changes may not solely arise from fish number surges. Enhanced fish populations might relate to additional, more suitable habitats, attracting fish from other areas. Thus, deeper research into these dynamics is crucial for effective restoration strategies and sustainable aquatic ecosystem management (Polivka, 2022). However, recent studies emphasize the production versus attraction debate (Cresson et al., 2014; 2019). These studies employing carbon isotopes demonstrate fish biomass production using organic matter from pelagic sources, especially in the largest Mediterranean AR system. They highlight ARs' effectiveness in supporting biomass production and trophic organization within ecosystems (Cresson et al., 2019). Invertebrate species' direct reliance on locally produced organic matter, primarily from filter-feeding organisms on ARs, suggests pelagic sources' significant contribution to organic matter. Stable isotope ratios confirm ARs as a food source, positioning fishes within the trophic network, reliant on AR-provided resources. This holistic view of ARs' ecological dynamics forms a valuable foundation for future research and informs coastal zone management strategies encompassing both natural and ARs (Koeck et al., 2011; 2014).

In summary, detailed studies exploring structure/complexity and species/community prevalence relationships are essential. Our underwater video-imaging protocol offers advantages over traditional diver surveys. This research significantly contributes to the AR debate in marine ecosystems. It effectively demonstrates ARs' role in supporting biomass production and vital food sources for fish populations, emphasizing their importance in managing damaged coastal areas, potentially enhancing biodiversity, fisheries, and eco-tourism. The positive impact of high-complexity artificial reefs on marine succession and biodiversity carries significant implications for marine conservation strategies, particularly within marine protected areas (MPAs) and fisheries management. These artificial reefs serve as vital habitats, fostering a diverse array of marine organisms by mimicking natural reef environments. They promote biodiversity by providing shelter and refuge for various species, including corals, algae, and fish, thus enhancing overall ecosystem health. Moreover, artificial reefs act as important nursery and feeding grounds for fish, supporting enhanced fish stocks and contributing to sustainable fisheries management. Additionally, these reefs facilitate habitat connectivity, allowing marine organisms to migrate between natural reef systems, thereby promoting genetic diversity and ecosystem resilience. Integrating high-complexity artificial reefs into MPA design and fisheries management strategies offers multiple benefits, including the protection of sensitive marine habitats, sustainable fisheries practices, and the conservation of biodiversity. Overall, the positive influence of artificial reefs underscores their potential as valuable tools for marine conservation and resource management in the face of increasing anthropogenic pressures.

While the results are promising, highlighting the potential of HCARs in marine restoration efforts, the call for extended monitoring underscores the complexity of artificial reef ecosystems and the need for cautious interpretation of short-term findings. Future research should aim to address the identified gaps, particularly regarding long-term ecological impacts, to better inform conservation and management practices. Future research should focus on long-term ecological outcomes, including potential changes in species composition, biodiversity, and the artificial reefs' physical and chemical impacts on the surrounding marine environment.

3 Materials and Methods

The HCARs Parc is situated at a depth of 20 meters within the Marine Reserve Colls i Miralpeix, Costes del Garraf, located 4 km off the Garraf coast in Catalonia, Spain (Figure 3A; Figure 3B). The area saw the deployment of a series of HCARs, initiating a seasonal ecosystem study aimed at assessing biodiversity changes and enhancements. Geode construction employed polyester fibre moulds with external metal reinforcement, followed by the construction of 24 mass concrete pieces. To anchor the geode modules to the seabed of the port of Vallcarca (Garraf), professional divers utilized hydrostatic balloons of 10 000 litres inflated by an air compressor, with subsequent re-floating. Upon re-floatation, precise repositioning occurred utilizing a submetric GPS global radio positioning system and buoy fields as references, leading to the sinking of each module to its designated location – either on the seabed or at corresponding plant levels. The installation consisted of 24 geodes, including a central geodes area (CGA) comprising 10 modules – 5 at the lower and 5 at the upper level –alongside a first radial ring of 4 modules surrounding the central area and a second radial ring consisting of 10 modules encircling both the central and first ring areas (Figure 2A; Figure 2B; Figure 2C; Figure 2D).

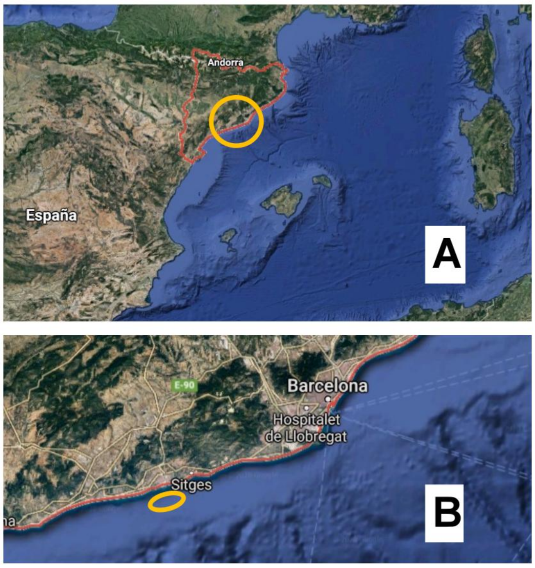

Figure 3 The western Mediterranean and the included Catalan Sea (A); Costes del Garraf MPA (B)
Note: Area where the study was conducted (indicated by the red circle) in front of the coast of Sitges, and the Colls i Miralpeix

This innovative HCAR model has not been previously attempted in the Mediterranean seabed for marine biodiversity restoration or elsewhere globally (to our knowledge). A specific image acquisition protocol was developed for fish species sampling within this heterogeneous environment. The study spanned three consecutive seasons – autumn, spring, and summer – selected for their distinct environmental conditions and biological activity. Fixed transects were established within the HCAR for underwater surveys during each season, conducting visual censuses to record marine species' presence and abundance. Additionally, the Shannon-Weaver

Diversity Index was calculated to assess species diversity within the reef ecosystem.

Five video transects (zone A; zone B; zone C; zone D; zone E) were systematically selected to encompass a spectrum of complexity within the habitat. The objective was to procure a comprehensive array of images and videos depicting the surrounding environment, aiming to capture a diverse spectrum of species. These zones are delineated as follows: A) Central core HCAR, B) Interior of the central core HCAR, C) Individual HCAR, D) Interior of individual HCAR, and E) Sandy bottom hosting *C. racemosa* (Figure 2A; Figure 2B; Figure 2C; Figure 2D). While the water column was evaluated in some cases, the data was not included in the analysis. Notably, video images were acquired from October to August at seasonal intervals (autumn, spring, and summer) to study temporal abundance variations across seasonal and spatial scales. Scuba divers meticulously captured video footage both within and outside the AR area throughout these seasons, although winter recordings were absent due to adverse sampling conditions. Species identification was conducted using the comprehensive Froese and Pauly (2019) web database. For illustrative purposes, an example of fish species identification can be found (Figure 4). A sequence of approximately 5-second video intervals was established to facilitate quantification and comparative analysis of fish assemblage descriptors. To manage large fish counts, observations exceeding 20 were capped (Tessier et al., 2004; Condal et al., 2012). Trophic level determination focused only on species identifiable at the genus and species levels.

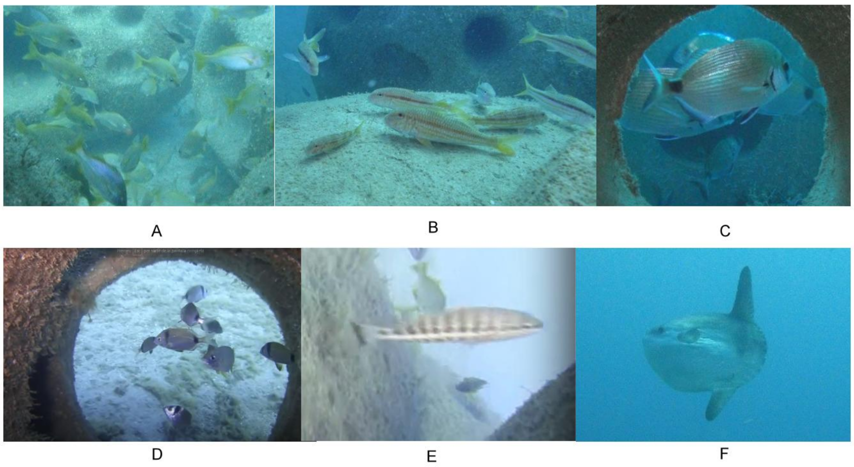

Figure 4 Examples of images for fish species identification
Note: *Pomadasys incisus* (A), *Mullus surmulletus* (B), *Diplodus sargus* (C), *Dipludus vulgaris* (D), *Serranus cabrilla* (E), *Mola mola* (F)

Community parameters per video interval sample included total fish count, distinct fish species count, fish species abundance, computation of Shannon-Weaver Diversity Index (H’). In accordance with the methodologies outlined by Shannon and Weaver (1949) and Krebs (1989), the computation of the Shannon-Weaver Diversity Index (H') involved several steps, with each H' calculated for every 5-second video interval. Initially, data collection encompassed recording the presence of species in video intervals. Subsequently, proportions of individuals for each species were calculated by dividing the number of individuals of a species by the total number of individuals observed across all species within each 5-second interval. These proportions were then subjected to natural logarithm transformation to handle the continuous nature of the diversity measure. Multiplying each proportion by its corresponding natural logarithm yielded values, which were summed across all species to obtain a cumulative value. Finally, the negative Shannon-Weaver Index was derived by multiplying the sum by -1, resulting in the Shannon-Weaver Diversity Index (H'). This approach facilitated a detailed assessment of species diversity dynamics over time, with higher H' values indicating greater diversity within each interval. In addition, we investigated the trophic structure of the ecosystem by determining the Trophic Level per species (TL) following the framework established by Pauly and Watson (2005). This involved assessing the position of each species in the food web based on its feeding habits and interactions. Both the Mean Trophic Level across all recorded data and the Weighted Mean Trophic Level, which takes into account the frequency of each species occurrence, were computed. These trophic level calculations provide insights into the energy flow and trophic relationships within the ecosystem, shedding light on its overall structure and functioning. The results of these analyses (Table 2), offering a comprehensive overview of the trophic dynamics observed in the study area. Visual count variations across seasons were represented via histograms and analyzed using SPSS statistical software. Due to dataset conditions not meeting parametric or non-parametric criteria, an exhaustive statistical analysis comparing measured parameters across video transects was not conducted. Acknowledging potential data errors, a deliberate approach was adopted to manage uncertainties and facilitate comparative analyses.

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