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Research Article

Experimentation on the Coastal Marine Habitat Restoration through Ecological Engineering: Creation and Test of Coastal Nurseries in the Mediterranean

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Abstract

The degradation of coastal marine habitats and biodiversity loss pose significant ecological challenges, requiring restoration efforts. In June 2024, the European regulation on nature restoration established a framework for managing and restoring these ecosystems. To address the scale of this task and limited experimental resources, the CREANURS program, led by the University of Corsica, was launched to test micro-habitat prototypes targeting key marine species. The project aims to enhance scientific and technical knowledge to optimize the restoration of small coastal habitats in the Mediterranean. Six types of micro-habitat prototypes were designed and tested *in situ* at the port of Porticciolo (Haute-Corse, France). Monitoring included structural changes, colonization by fauna and flora, and acoustic characterization. Results showed most prototypes lacked sufficient physical resistance to exceptional storms, limiting monitoring duration. Biological colonization results were mixed; most micro-habitats were less effective than natural environments for mobile fauna. However, the FracFoam prototype showed promise as a shelter for a diverse detritivorous benthic community, similar to that associated with Posidonia litter. Acoustic monitoring revealed a rich benthic biophony, ranking the site among the most efficient in the French western Mediterranean. Despite heterogeneous results and environmental constraints, FracFoam stands out with an estimated 80% efficiency for restoring degraded benthic habitats, offering new perspectives for facilitating natural Posidonia colonization.

Abbreviations

MH: Micro-Habitat; MHs: Micro-Habitats

Introduction

Benthic marine habitats, characterized by a diversity of substrates, environmental conditions, and engineered species, fulfill vital ecological functions such as nursery grounds, spawning grounds, feeding grounds, and protection [1-3]. These environments harbor rich biodiversity and provide essential ecosystem services [4,5]. However, they are subject to increasing anthropogenic pressures, particularly in coastal areas, including pollution, unsustainable recreational uses, artificialization, and fishing [6]. These degradations can exceed the natural recovery capacity of ecosystems, making a return to a previous state impossible [7-11]. The 2020 European assessment indicates that 81% of European habitats are in poor condition, despite existing protection policies [12]. This situation underscores the need for additional measures, leading to growing interest in the ecological restoration of marine ecosystems [13]. Restoring ecological functions is identified as one of the greatest challenges in marine ecology. In response, the United Nations Decade on Ecosystem Restoration (2021-2030) calls for the revitalization of ecosystems globally [14].

It is in this context that the CREANURS program, led by the University of Corsica, and financed by the Water Agency (a

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French public institution), is being implemented. The objective is to develop and experimentally test small-scale artificial habitats, called "microhabitats," specifically designed for the restoration of degraded or destroyed benthic coastal habitats. These microhabitats aim to function as "nurseries" for the young stages of marine organisms, "spawning grounds" for breeders, or "specific" habitats to test attractiveness and direct natural recruitment toward species of economic or heritage interest. The project thus seeks to replace or complement degraded natural habitats to increase or maintain local marine biodiversity and fish populations. The experiment specifically targeted Posidonia, an emblematic Mediterranean species.

Materials and methods

The CREANURS program consisted of the design of six different types of artificial microhabitats, and the fabrication, immersion, and *in situ* experimental testing of 56 modules. The target organisms for these experiments were echinoderms (*Paracentrotus lividus*), cephalopods (*Octopus vulgaris*, *Sepia* sp.), post-larvae and juvenile fish, and invertebrates in general.

The prototype design, carried out in collaboration with two innovative French companies SM2 Solutions Marines and Architeuthis, took into account the site's environmental constraints, the intended function (nursery, spawning ground), and the target species. Various materials, including recycled and plant-based materials, were used and tested for their attractiveness. The six concepts developed were:

- Local macroalgae wall (Nursery for juvenile fish/invertebrates, on dock/rockfill).
- FracFoam (Nursery for juvenile fish/invertebrates, on sand).
- Sea urchin microhabitat (Nursery for juvenile sea urchins, on sand).
- Cephalopod microhabitat (Spawning ground/Nursery for cephalopod spawners, on sand).
- Artificial seagrass bed (Spawning ground/Nursery for fish/invertebrates, on sand).
- Totem (Nursery for juvenile fish/invertebrates, on rock dike).

The site chosen for the experiment is the port of Porticciolo (Cap Corse, France), selected for the quality of its environment, its ease of access, its monitoring potential, and its educational showcase (Figure 1). An experimental area was set up *in situ* to test the attractiveness of micro-habitats by natural capture. The modules were positioned in quayside, seawall rockfill, and natural sandy areas, depending on the environmental parameters and the target species. An initial installation of the modules took place in April 2017, followed by a partial or total reinstallation in June 2018 following damage caused by storms. An initial state of the site was carried out by the Creocean company in April 2017 to serve as a reference [15]. The installation of the modules, with a limited footprint (footprint less than 10 m^2, weight less than 80 kg, volume less than 2 m^3, height less than 1.5 m) and a lifespan calibrated for the experiment (1 year of immersion), was carried out by the design companies and the Stella Mare team, with fixings adapted to the substrate (harmony screws on sand, drilling then resin on dike and rockfill).

The scientific monitoring was planned over approximately 12 months, although it was heterogeneous due to the necessary reinstallations. The monitoring protocol was defined in collaboration with the companies Creocean, Chorus, SM2

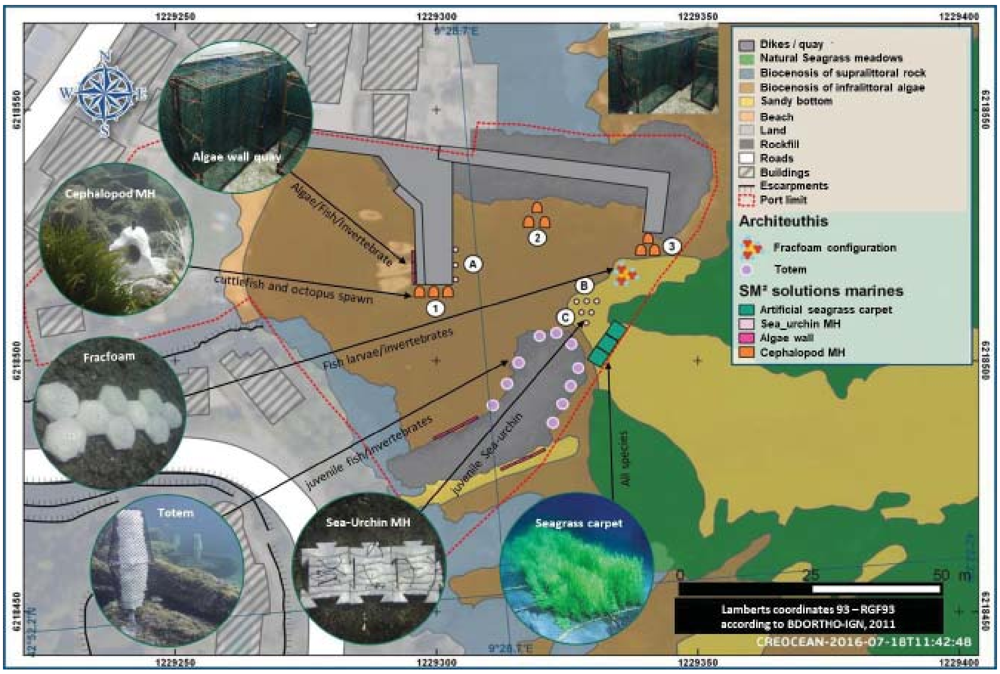

Figure 1: Location of the various module installations within the experimental area of the small port of Porticciolo (Cap Corsica, France).

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Solutions, Architeuthis, and engineers from the Stella Mare platform at the University of Corsica [15]. It included:

- Monitoring of structural changes (deterioration, clogging, fixations) by the Stella Mare team.
- Monitoring of the fixed flora and fauna colonization (permanent quadrats, photographs, species counts) by Creocean.
- Behavioral monitoring of mobile fauna (fish, crustaceans, echinoderms, mollusks), primarily post-larval/juvenile and reproductive fish populations, by the Stella Mare team. This monitoring, based on the visual census method [16], involved visual counts by diving into the targeted modules and reference sites, with species identification enumeration and size estimation. Fish monitoring was carried out monthly, or even bimonthly in spring/summer.
- Acoustic monitoring using passive acoustics in partnership with the Chorus Institute. Hydrophones were positioned inside (P1, P2, P3) and outside the port (P4, P5, natural habitats) to characterize the acoustic environment and extract the biophony of benthic invertebrates and fish [17,18]. Measurement sessions were carried out in April and October 2017 [15]. The acoustic monitoring employed passive acoustic methods to evaluate the biodiversity of marine environments, utilizing biophony as a proxy for the state of animal communities. Data were collected using RTSYS SDA 14 recorders and HTI 92 hydrophones, deployed as single units and as compact four-hydrophone arrays to enable sound source localization. The processing of biological acoustic data for both benthic invertebrates and fish involved specific algorithms tailored to their distinct sound characteristics. For benthic biophony, which consists of short, strong impulses generating wide-band spectra above 1.5 kHz, an optimal detector was used, combining a high-pass filter with an energy detector that compares signal energy against the estimated noise floor. This methodology, including the detailed algorithms for the detection and description of benthic biophony, is thoroughly described in a scientific article [18]. In contrast, ichthyological biophony, characterized by successions of rapid impulses predominantly in the 50 Hz to 1500 Hz range, required a different approach to mitigate masking by boat noise. Instead of detecting individual impulses, the methodology focused on identifying 'impulse trains' exhibiting a repetition rhythm, adapted from cetacean click train detectors. Furthermore, the use of compact four-hydrophone arrays allowed for the localization and mapping of detected biological sounds in 3D (azimuth and elevation), which is crucial for distinguishing sound production originating from artificial nurseries versus adjacent natural habitats given their acoustic proximity.

About trophic functioning, we assigned a trophic code to each species according to the Word 1990 method, which is based on three criteria: the type of nutrient material collected (size, nature); the compartment in which this material is collected (water column, surface or sub-surface of the sediment); the capture method used to collect the material (passive or active capture from appendages, capture by pumping and filtering, capture by searching the substrate, habitat use). Based on these three criteria, different groups and trophic codes are established:

- Group 1: Suspension feeders microphagous detritivores that feed on very small particles suspended in the water column and are generally abundant in healthy, well-ventilated environments;
- Group 2: Surface microphagous detritivores that feed on very large particles but are deposited on the bottom or integrated into surface sediments;
- Group 3: Deposit feeders (macrophages) that feed on larger particles deposited on the bottom or incorporated into the sediment; this group includes most carnivores;
- Group 4: Species characteristic of highly degraded anaerobic environments.

The effectiveness of the tested prototypes is evaluated according to 4 main criteria: (i) their physical resistance (structure and fixation), (ii) their implantation site (biological interest and environmental constraints), (iii) their colonization and contribution of biological biomass (animal and plant) compared to the natural reference zones and (iv) the species of interest recruited according to the targeted species and ecosystem services provided. Depending on the results obtained for each of the characteristics composing our criteria taken into account above, relative effectiveness for each of our prototypes was estimated according to an effectiveness scale divided into 6 classes: 0% - 10% Poor, 10% - 30% Very Unsatisfactory, 30% - 50% Unsatisfactory, 50% - 70% Fairly Satisfactory, 70% - 90% Satisfactory, above 90% Very Satisfactory.

Results

Micro-habitat structure

Most prototypes showed insufficient resistance to the strong hydrodynamic conditions and exceptional storms that occurred in 2017 (Ana and Bruno in December) and 2018 (Carmen and Eleanor in January, Adrian in October, and Flora in December), particularly in the shallow and exposed port of Porticciolo. The major weak points were the fastening systems. The most affected prototypes were the Totems and Cephalopod Micro-habitats, which were quickly torn off or destroyed. The Seaweed Walls also suffered significant structural damage. The FracFoams were severely affected by the storms, with some modules displaced or destroyed, but maintained relative integrity compared to the others. The Sea Urchin Micro-habitats and the Artificial Seagrass Bed withstood the storms better, especially the Artificial Seagrass Bed positioned deeper outside the port, although it showed signs of progressive deterioration of its fronds. The damage led to the interruption of biological monitoring from December 2017 and November 2018, and the need for a second installation in June 2018.

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Colonization of fixed flora and fauna

Overall results are mixed. The Seaweed Walls did not show conclusive results, as the algae did not maintain themselves sustainably. The Artificial Seagrass achieved epiphytic colonization comparable to the natural seagrass on its fronds, but the benthic community colonizing the artificial mat was very different and had low abundances and biomasses. The Sea Urchin Microhabitats were ineffective at attracting juvenile sea urchins and limited for colonization by hard substrate species, being easily covered by sediment. The Cephalopod Microhabitats were mainly colonized by common algae and did not attract any spawning or adult octopus. The FracFoam prototype showed little interest in external epiphytic flora and fauna, but the interior of the modules was colonized by abundant and diverse benthic fauna (small crustaceans, annelids, juvenile sea urchins, sea cucumbers), attracted by trapped plant debris. This benthic community is similar to that of natural Posidonia litter and mattes (Figure 2). Composed of small detritivores dominated by amphipods, isopods, and polychaetes, it is very similar to the communities living on mattes and in Posidonia litter. Among the 79 species recorded in the FracFoam and the 97 species recorded in the natural herbarium in 2018, 40 species are common to both lists. There is a strong similarity between the two data sets for the results of species richness, total abundance, and Shannon index (Table 1). The biomass also differs little between the two data sets. Furthermore, the results on the distribution of densities by taxonomic group are very similar; the results are very similar to those found in the FracFoam (Figure 3). FracFoam is home to more deposit-feeding species (Group 3) while the natural seagrass bed is dominated by detritivorous species (Group 2). Both habitats have virtually no Group 4 species, which indicates very deteriorated conditions in terms of eutrophication.

Behavioral monitoring of mobile fauna

The behavioral monitoring of mobile fauna, mainly fish, was made very heterogeneous by the successive degradations

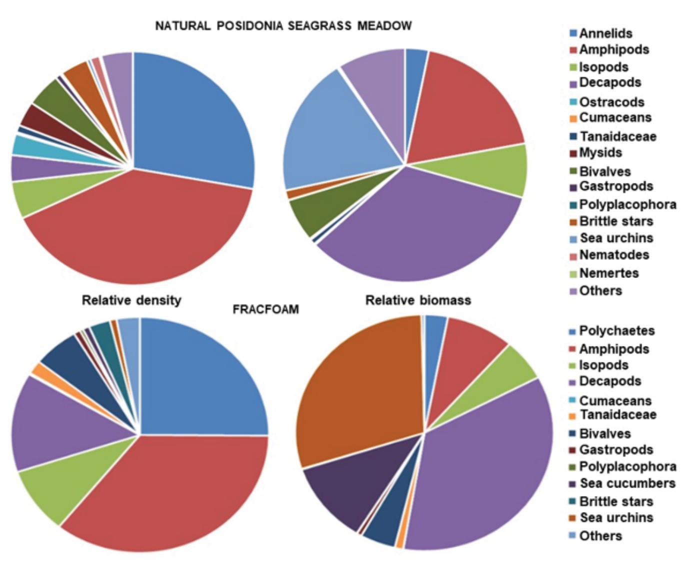

Figure 2: Respective contribution of taxonomic groups to total density and biomass in natural seagrass meadow and FracFoam (August 2018).

Table 1: Comparison between Fracfoam litter and natural *Posidonia* litter and mattes.

Parameters	Fracfoam	Natural *Posidonia* litter
Specific richness (number of species)	79	97
Abundance (number of individuals)	482	406
Biomass (g)	2,80	1,44
Shannon index (bits)	5,3	5,7

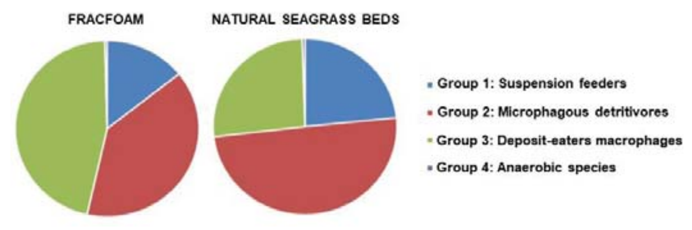

Figure 3: Importance of the respective trophic groups between Fracfoams and natural reference seagrass beds (% of the main abundance).

of the structures due to bad weather conditions and exceptional storms that occurred during the project period, thus limiting the effective duration of monitoring from 4 to 19 months depending on the prototype. These observations focused mainly on the summer period, with some sessions in late spring or early autumn. Overall, the results showed that no artificial micro-habitat proved more effective than the surrounding natural environment in attracting and maintaining mobile fauna in terms of species diversity and fish abundance. The natural reference areas generally presented higher species diversity and number of individuals, with typically 1 to 4 species and 14 to 51 individuals observed per dive on the natural sites, compared to 1 to 2 species and 4 to 16 individuals on the artificial habitats (Figure 4). The only prototype that potentially showed results superior to those of its reference was the "Seaweed Wall" positioned on the outer dike (Figure 5). This module presented a greater diversity and an overall higher number of individuals compared to its reference area, with an average of 1.7 species versus 1.3 and 7.3 individuals versus 4.95. However, this observation is based on a very short monitoring time of only 4 months before the destruction of the module, which prevents definitive conclusions from being drawn on its effectiveness. For species of interest to commercial fishing, such as *Diplodus* sp. and *Pagelus acarne*, the natural reference areas proved more attractive than the artificial habitats tested. Among the artificial habitats, the "Artificial Seagrass Carpet" presented the values closest to those of its natural reference site for these species. It is also noted that the visual census monitoring method using scuba equipment may have limitations due to its punctual and potentially disruptive nature to the environment.

Acoustic monitoring

Carried out in April and October 2017, they showed abundant biophony (benthic and ichthyological) at all measurement points (Figures 6,7). Benthic biophony is particularly abundant inside the port of Porticciolo, where the artificial structures are installed. This abundance ranks the CREANURS site among the richest sites in benthic biophony in the French western Mediterranean, compared to data from the CALME network

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[19] and other restoration projects (Tables 2,3). Ichthyological biophony is also abundant and rich, dominated by the "kwa" sound emitted by the scorpion fish. The CREANURS site is in the same range of otoacoustic scores as other ecological restoration sites studied by Chorus in terms of ichthyological biophony. The acoustic analysis also revealed significant anthropophony due to boat passages. The data suggest the existence of different fish communities between the port and the seagrass bed, evolving with the season, but the monitoring period (two seasons) was too short for statistically significant conclusions.

Prototype effectiveness

The results obtained for the estimated overall efficiency for each prototype are as follows: 80% for FracFoam, 71% for the “Outdoor Dike” version of the algae wall, 61.8% for the

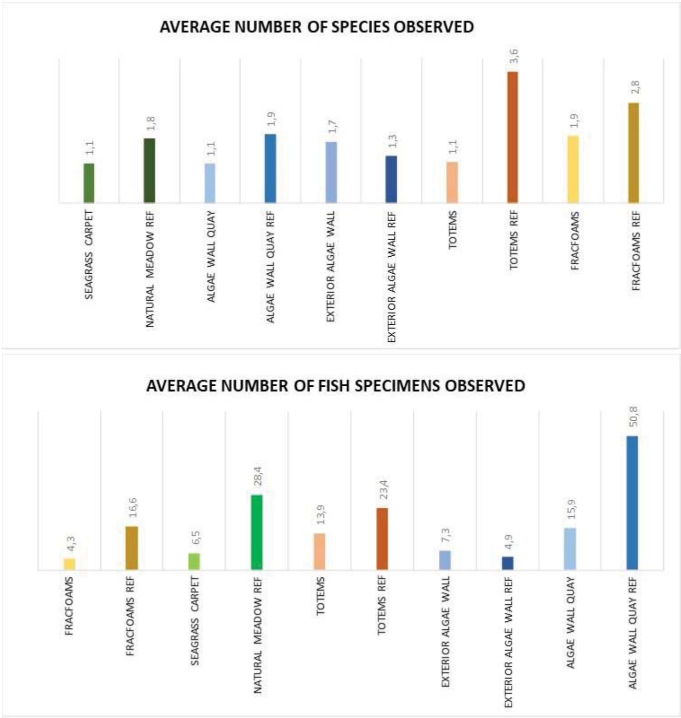

Figure 4: Average number of fish species and specimens observed for each microhabitat type compared to its corresponding reference site.

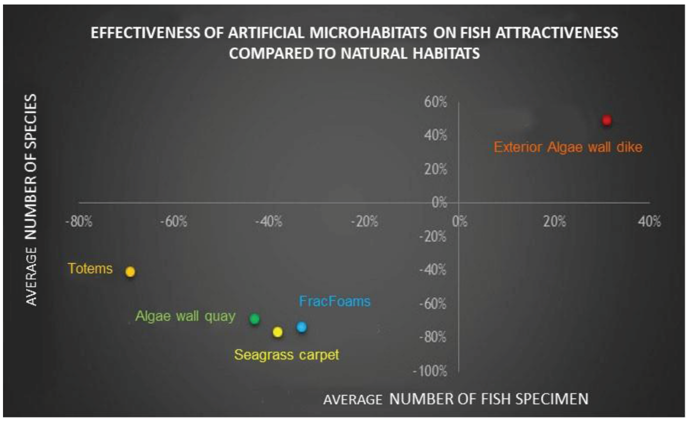

Figure 5: Effectiveness of artificial microhabitats on the attractiveness of fish compared to their natural habitats.

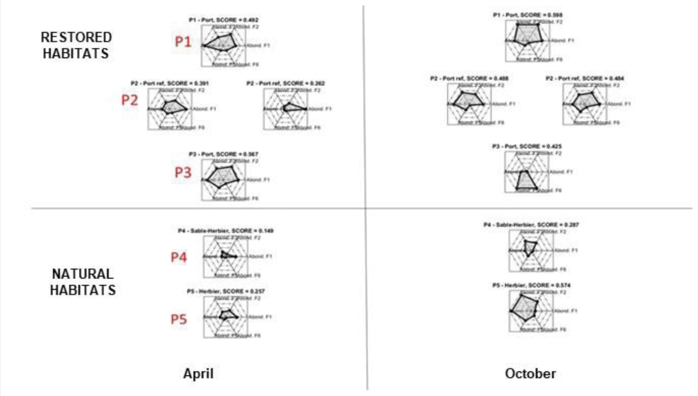

Figure 6: Comparison of benthic bioacoustic scores in the port of Porticciolo.

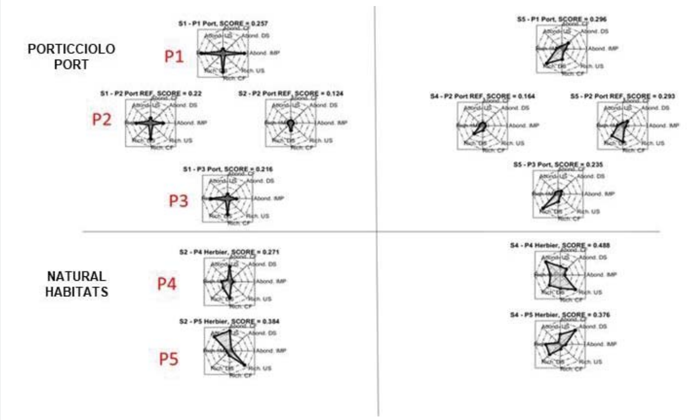

Figure 7: Comparison of fish bioacoustic scores in the port of Porticciolo.

Table 2: Abundances of benthic pulses from CREANURS sites compared to 3 ecological restoration projects.

Measuring position	Number of pulses/hour
CREANURS – P1 (port)	142 962
CREANURS – P2 (port)	107 829
CREANURS – P3 (port)	106 997
CREANURS – P4 (sand upper limit seagrass)	125 288
CREANURS – P5 (seagrass meadow)	100 735
REXCOR* – village C	90 673
REXCOR* – village B	68 924
REXCOR* – village A	37 943
REXCOR* – village D	84 003
ORREA/SICIE** – P1	3853
ORREA/SICIE** – P2	12 354
ORREA/SICIE** – P3 (seagrass meadow)	22 530
Bob*** – Buoy offshore	88 537
Shellfish table*** – pond	73 897
Reefs ***E4 Leucate (15 years)	112 222
Reefs ***Leucate (15 years)	91 675

* REXCOR Project: SEABOOST's ecological restoration project at the Calanques National Park site (Cortiou Calanque) in front of the Marseille wastewater treatment plant discharge.
** ORREA Project: ECOCEAN's ecological restoration project at the Cap Sicié site in front of the Amphitria wastewater treatment plant discharge.
*** ECOCEAN's CONNEXSTERE and COMPLEXIFICATIONS projects, and collaboration with Cefrem, on the artificial reefs of Leucate, in the Leucate lagoon, and on a buoy called BOB installed offshore.

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Table 3: Ichthyological biophony scores of CREANURS sites in comparison with three ecological restoration projects.

Measuring position	Abundance/hour	Richness
CREANURS – P1 (port)	8,4	15
CREANURS – P2 (port)	6,4	9,5
CREANURS – P3 (port)	6	12,5
CREANURS – P4 (sand upper limit seagrass)	113,2	16,5
CREANURS – P5 (seagrass meadow)	160,2	8
REXCOR* – C	16,6	15,8
REXCOR* – B	29,6	24,5
REXCOR* – A	12,6	12
REXCOR* – D	7,3	10,4
ORREA**/SICIE – P1	29,1	10,3
ORREA**/SICIE – P2	57,5	11
ORREA**/SICIE – P3 (seagrass meadow)	258,8	17,7
BOB*** – Buoy offshore	12,4	6
Reefs*** E4 Leucate (15 years)	5	13,5
Reefs*** Leucate (15 years)	6,7	16,5
Shellfish table *** - Pond	13,2	19,5

* REXCOR Project: SEABOOST's ecological restoration project at the Calanques National Park site (Cortiou Calanque) in front of the Marseille wastewater treatment plant discharge.
** ORREA Project: ECOCEAN's ecological restoration project at the Cap Sicié site in front of the Amphitria wastewater treatment plant discharge.
*** ECOCEAN's CONNEXSTERE and COMPLEXIFICATIONS projects, and collaboration with Cefrem, on the artificial reefs of Leucate, in the Leucate lagoon, and on a buoy called BOB installed offshore.

Seagrass Mat, 31% for the "Quay" version of the algae wall, 23.6% for the Totems, 21.8% for the Sea Urchin micro-habitat and 3.6% for the Cephalopod micro-habitats. The summary table grouping these results (Table 4) will allow the reader to better understand the efficiency on a finer scale, in order to identify areas for improvement for better results in future tests.

Discussion

The evaluation of the effectiveness of the CREANURS prototypes, based on physical resistance, the implantation site, colonization/biomass, and the targeted species/services provided, was strongly impacted by the exceptional and repetitive nature of the storms over the study period. The low physical resistance of the majority of prototypes, mainly due to fixing systems unsuited to the high hydrodynamics of the site, severely limited the duration and robustness of the biological monitoring. The implantation site itself, although presenting notable biological qualities according to the acoustic studies, proved to be very exposed to hydrodynamic constraints, a factor initially underestimated, notably due to errors in identifying the underlying substrate during the implantation phase. The proposed improvements focus on the imperative need to strengthen the structural strength of prototypes, particularly the fastening systems, to adapt them to the constraints of exposed environments. Complete redesigns are recommended for concepts such as the MH Sea Urchins and MH Cephalopods.

Table 4: Effectiveness estimation of each prototype tested based on the different criteria taken into account.

Effectiveness criteria	Algae wall quay	Algae wall dike	Grass carpet	Sea Urchin MH	Cephalopods MH	Totem	FracFoam
Duration of scientific monitoring (in months)	6+7	4	17	17	13	8+5	9+4
Physical resistance (structure)	--	--	-	++	---	---	++
Physical resistance (fixation)	-	-	++	++	---	---	-
Implantation site (biological interest)	+++	+++	+++	-	---	+++	+++
Location (environmental constraints)	--	--	++	-	---	---	-
Colonization (target species)	-	+++	-	---	---	+	++
Colonization (non-target species)	--	+++	++	---	--	--	++
Biomass contribution (target species)	-	+++	-	---	---	+	++
Biomass contribution (non-target species)	--	++	+	---	--	--	+++
Richesse spécifique/Abondance (espèces ciblées)	-	+++	+	---	---	-	++
Ecosystem service provided (targeted objective)	-	++	+	---	---	--	+++
Ecosystem service provided (objective not targeted)	-	++	+	---	---	-	+++
Overall efficiency	- 31 %	++ 71 %	+ 61,8 %	-- 21,8 %	--- 3,6 %	-- 23,6 %	++ 80 %

EFFICIENCY SCALE

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The results of mobile fauna monitoring, although limited in time for many prototypes, suggest a generally lower effectiveness than that of natural reference environments, including for species of fisheries interest. Only the Outdoor Seaweed Wall showed potential for increasing diversity and abundance, but over a monitoring period that was too short to be conclusive.

Regarding the colonization of fixed fauna and flora, results vary depending on the concept. The Seaweed Walls, Sea Urchin MHs, and Cephalopod MHs showed little biological interest. The Seaweed Walls received limited long-term monitoring due to their structural degradation. The Sea Urchin MHs appeared unsuitable for juveniles, owing to both their design and placement; the concept proved ineffective regardless of whether the site functioned as a source or sink population. Similarly, the Cephalopod MHs were also poorly positioned. A more effective approach would have been to integrate it into the rocky substrate or the breakwater structure itself, in order to place it near other small cavities that support foraging by adult individuals through the presence of associated sheltering fauna. The Artificial Seagrass had limited success despite epiphytic colonization comparable to nature, its benthic composition being different and its artificial material presenting disadvantages. The estimated effectiveness for each prototype reflects these observations, placing FracFoam (80%) in the lead, followed by the Algae Wall External Dike (71%) and the Seagrass Mat (61.8%), while the MH Sea Urchins, Totems, and MH Cephalopods obtain low scores (21.8%, 23.6%, 3.6% respectively).

The FracFoam prototype stands out for its ability to attract and shelter an abundant detritivorous benthic community, similar to that of Posidonia litter, including potentially interesting species such as juvenile sea urchins and sea cucumbers. Its operation as a "particle trap" reproduces an essential ecological function of natural seagrass beds. Although the benthic communities found in the FracFoam artificial litter and in natural Posidonia oceanica litter and mat exhibit broadly similar taxonomic compositions—dominated by small crustaceans (amphipods, isopods, tanaidaceans, decapods, ostracods) and polychaetes—clear functional differences emerge, particularly in terms of trophic structure and nutrient cycling. In natural Posidonia systems, the trophic balance between surface-feeding microphagous detritivores (Group 2) and macrophagous deposit feeders (Group 3, including many carnivores) is more evenly distributed, reflecting a structurally complex and ecologically mature habitat [20,21]. By contrast, the FracFoam environment tends to support a higher proportion of Group 2 taxa, which preferentially exploit fine particulate organic matter on or near the substrate surface. This trophic bias may indicate an earlier successional stage, with a reduced capacity for processing coarse detritus, thereby limiting the functional equivalence of FracFoam to natural Posidonia litter. Consequently, while FracFoam effectively sustains detritus-based trophic pathways, its ecological role may be more focused on short-term organic matter recycling, with a lower potential for carbon sequestration and organic matter export to adjacent coastal systems. Nonetheless, FracFoam may offer significant advantages for the passive restoration of degraded Posidonia meadows. By providing physical substrate stability and promoting the establishment of a benthic community dominated by small detritivores typically associated with Posidonia litter, it could enhance the natural recolonization of the seabed by Posidonia rhizomes. In this context, FracFoam may serve as both a temporary functional analog of seagrass litter and a facilitator of long-term meadow recovery in physically impacted habitats.

The estimated effectiveness scale for each prototype reflects these observations, placing FracFoam (80%) in the lead, followed by the Seaweed Wall External Dike (71%) and the Seagrass Mat (61.8%), while the Sea Urchin, Totem, and Cephalopod MHs obtained low scores (21.8%, 23.6%, and 3.6%, respectively).

The proposed improvements focus on the imperative need to strengthen the structural strength of the prototypes, particularly the attachment systems, to adapt them to the constraints of exposed environments. Complete redesigns are recommended for concepts such as the Sea Urchin and Cephalopod MHs.

Conclusion

The CREANURS program demonstrated the importance of ecological engineering for restoring coastal marine habitats but also highlighted major technical challenges, including the resistance of structures to extreme environmental conditions. Most of the prototypes tested in the exposed port of Porticciolo succumbed to storms, limiting the assessment of their long-term biological effectiveness. Although the impact of such storms remains exceptional, climate change is expected to increase both the frequency and intensity of conventional storms. Future experiments conducted in shallow coastal areas should therefore incorporate improvements to fixed systems (such as storm-resistant designs, reinforced anchoring, or integration into port infrastructure), and favor more sheltered sites with respect to wave exposure.

Despite these constraints, some concepts have shown potential. FracFoam has proven the most promising by providing a favorable habitat for a rich and diverse detritivorous benthic community, similar to that of Posidonia litter. This characteristic positions it as a potential tool, not for the transplantation of Posidonia, but to facilitate the natural colonization of degraded meadows by providing physical support and an associated community favorable to the development of rhizomes. Additional research and a redesigned version of the FracFoam system (FracFoam II) are planned to further investigate its ecological potential. A long-term monitoring strategy (> 2 years) is proposed to evaluate the persistence and reliability of its ecological functions, to convert the preliminary "80% efficiency" into quantifiable ecological metrics—such as carbon sequestration capacity and juvenile survival rates—relevant to habitat restoration and ecosystem service assessments. Deployed in a highly exposed location, the seaweed wall exhibited promising outcomes, indicating potential for the short-term recovery of mobile fauna. However,

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the assessment was limited to four months due to significant data loss caused by structural damage during exceptional storm events. These preliminary findings support the need for further trials, contingent upon structural enhancements to improve resilience under high-energy conditions.

The acoustic results confirmed the site's biophonic richness, highlighting its potential for restoration, and the value of passive acoustics as a complementary monitoring tool, although further development is needed for more precise sound attribution to specific structures.

In conclusion, the CREANURS project, despite the challenges encountered, laid essential scientific and technical foundations. It identified the most promising prototypes (notably FracFoam) and highlighted the crucial need to integrate structural robustness and site adaptation as top priorities for the future success of restoration initiatives based on ecological engineering. Longer monitoring periods and the use of complementary methods will be necessary to confirm the ecological effectiveness of the improved concepts. This is only a preliminary study of testing the effectiveness of prototypes in terms of structure and biological attraction. The second stage will indeed have to take into account more in-depth and complementary aspects of the costs of construction, deployment, maintenance, and the evaluation of the large-scale reproducibility of prototypes that have passed this first effectiveness selection.

Conflict of interest

The technical details of the various prototypes cannot be presented here due to concerns regarding intellectual property and confidentiality of concepts that may be patented.

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