

RESEARCH ARTICLE

Assessing the ecological and aesthetic effectiveness of restoration interventions on coralligenous reefs

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Although tools for actively restoring marine habitats have advanced considerably, the capacity and timeframes for ecosystem recovery remain uncertain. Time and funding constraints, and lacking metrics to quantify the recovery process, represent the primary obstacles to evaluating restoration success. Here, we assess the recolonization dynamics of bare coralligenous reefs and the effectiveness of restoration actions, consisting of disturbance removal and transplantation of *Eunicella cavolini* and *Paramuricea clavata* colonies, following the Costa Concordia shipwreck disaster. We quantified transplantation efforts and assessed community dynamics, diversity, and aesthetic value at impacted and nearby control sites. Recolonization patterns were slow, characterized by an increase in species richness over time. Perennial encrusting algae led the recolonization of bare surfaces. Transplanted colonies showed a high survival rate and an increase in density and cover; in contrast, no natural recruitment was observed on the monitored reefs. The impacted reefs exhibited a steady increase in ecological metrics, although their values remained significantly lower than those of the control sites. Conversely, by 2020, the aesthetic value of the reefs in the impacted site had equaled that of the control sites. This work provides empirical evidence that disturbance removal and transplantation of erect-structuring species can support the recovery of structure and aesthetic perception of coralligenous reefs. Full recovery is unfeasible in a short time, underscoring the importance of long-term protection and monitoring efforts. Assessing the effectiveness of restoration initiatives should include evaluating their impact on cultural ecosystem services.

Key words: aesthetic score, diversity patterns, Mediterranean Sea, octocoral transplants, restoration success, restore biodiversity

Implications for Practice

- Recolonization dynamics of coralligenous reefs are slow and supported by larval settlement and encroachment from above concretion portions, but the full recovery remains unrealistic in the short term.
- Disturbance removal allows for a gradual increase of diversity patterns, with value ascribable to early-stage community development.
- Octocoral transplantation allows for the introduction of two species that did not show natural settlement and contributes to the rapid recovery of the aesthetic value of impacted reefs.
- Long-term protection and monitoring efforts are needed to ensure restoration effectiveness on coralligenous reefs.
- Evaluating the impact of restoration initiatives on cultural ecosystem services is crucial: this information can be integrated with traditional parameters used to assess the effectiveness of such interventions.

Introduction

Increasing human pressure and climate change are causing widespread, irreversible degradation of the world's oceans. Addressing this threat is crucial to prevent the ecological decline and loss of benefits that marine ecosystems provide to society. The urgency is recognized politically, with the UN launching

initiatives to reverse the decline in ocean health by 2030 and the EU approving the Nature Restoration Law in 2024, as part of the European Biodiversity Strategy. Scaling up interventions and their effectiveness requires identifying the details of coastal ecosystem restoration outcomes, technological advancements, and institutional agreements, as well as initiating the process for public and private capital investment (Waltham et al. 2020).

While our understanding of the effects due to disturbance factors and tools for active recovery has improved significantly over the past few decades, information regarding the capacity and timescales of marine ecosystems to recover remains unclear

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(Lotze et al. 2011). Limited time and financial resources, as well as lacking metrics, jeopardize our ability to adequately assess the effectiveness of restoration interventions (Fraschetti et al. 2021). To date, the outcome of habitat restoration efforts is assessed by quantifying the survival rate and demographic parameters of transplanted species (Basconi et al. 2020). This approach markedly diverges from the criteria defined by Ruiz-Jaen and Aide (2005), which encouraged the use of at least two variables within each of the three ecosystem attributes (i.e., diversity, vegetation structure, and ecological processes) that are linked to ecosystem functioning, as well as multiple reference sites to encompass the existing variation in ecosystems.

Mediterranean coastal hard bottoms play a crucial role in supporting ecosystems due to their extension and the diversity of habitats they host, among those recognized as biogenic reefs (Ballesteros 2006; Ingrosso et al. 2018). The extensive effect of disturbances on these ecosystems highlights the urgent need for a new, holistic, and integrated approach to enhance their health status (Bevilacqua et al. 2021). Several active restoration initiatives have been recently carried out aiming at the recovery of macroalgal assemblages (Cebrian et al. 2021; Orlando-Bonaca et al. 2021; Fabbri et al. 2023) and invertebrate populations (Musco et al. 2017; Ferranti et al. 2021; Casoli et al. 2022). Coralligenous reefs have been the focus of marine restoration efforts, particularly through the transplantation of octocoral species to establish complex multilayered habitats and restore ecosystem functions (Montseny et al. 2021; Casoli et al. 2021a; Topçu et al. 2023). The presence of a well-developed erect layer supports different ecological processes and their associated ecosystem functions (Gómez-Gras et al. 2021), and positively affects the aesthetic value of the coralligenous reefs as well (Tribot et al. 2016; Langlois et al. 2021).

The concept of aesthetics is transversal to several disciplines and has different declinations: in ecology, the aesthetics of the landscape is considered the pleasure experienced in observing individual species, assemblages, or natural landscapes (Swaffield & McWilliam 2013; Tribot et al. 2018). The observation of the environment triggers a cognitive response that generates an aesthetic experience in the viewer's mind, inspiring and contributing to well-being: nature's aesthetic experience is considered one of the major cultural ecosystem services (CES; Díaz et al. 2018). Considering the relationship between the aesthetic value of seascapes and biodiversity could open future perspectives in conservation biology and restoration ecology (i.e., Waechter et al. 2024). Langlois et al. (2021) reported that the aesthetic value of the coralligenous reefs is positively correlated with diversity indices, indicating that the greater the diversity, the higher the aesthetic value of the seascape. However, the composition of the assemblage can positively and negatively affect the aesthetic value of the reefs, potentially leading to an aesthetic bias in human perception of ecological value. This is related to the different features of each single species and the human preferences for images with large and distinct species that delineate objects more appreciable from the background (Tribot et al. 2016).

The present work has been developed following the Costa Concordia disaster and the restoration measures adopted to

remove disturbances and accelerate the recovery of coralligenous reefs within the wreckage area (Casoli et al. 2017, 2021a). The wreckage and the following salvage operations (2012–2015) caused shading, physical disturbances (due to the debris release from the wreck), and sediment deposition that affected the coralligenous reefs' integrity and ecological status. Then, an integrated approach was applied, including passive and active recovery actions, to respond to an impacted and anthropogenically changed environment. This aimed to remove pressures and accelerate the recovery of natural benthic ecosystems. The seafloor was accurately cleaned (2015–2017) to eliminate the disturbances mentioned above on the benthic habitats. A total of 25,000 t of grout and 8,935 t of fine sediments and debris leaked from the wreck were removed manually and through an air-lift pump by divers over an area of 86,000 m². Due to the cleaning phase, dead portions of coralligenous reefs were revealed, representing suitable bare substrate to follow natural recolonization processes and transplanting efforts (2018–2024; Fig. S1). Here, colonies of the octocorals *Eunicella cavolini* (Koch, 1887) and *Paramuricea clavata* (Risso, 1827) were transplanted to accelerate the recovery of the erect layer of the coralligenous assemblages.

Within this frame of reference, this study aims to assess (1) the recolonization dynamics of bare coralligenous reefs and (2) the short-term effects of active restoration actions in improving the ecological and aesthetic values of coralligenous reefs. To this end, we evaluated community composition and structure, and applied metrics that characterized ecosystem and perceptual attributes. The coralligenous assemblages at the site impacted by the Costa Concordia were compared to those from nearby natural reefs used as reference conditions. We hypothesized that successful restoration actions should lead to the recovery of ecological features and processes. Therefore, the smaller the difference between the diversity patterns and aesthetics of the restored and reference coralligenous reefs, the greater the short-term restoration success.

Methods

Study Area and Sampling Activities

The study was carried out along the east coast of Giglio Island (10.9214 N; 42.3649 E; Tyrrhenian Sea, Italy), within the area impacted by the Costa Concordia wreckage (Imp), and at three control sites taken as reference conditions (Le Scole: C1; Punta del Lazzaretto: C2; Secca della Croce: C3; Fig. 1). The three control sites well represent the seabed geomorphology of the eastern side of the island, consisting of two rocky ridges (C1 and C2) and a bank (C3) of lower Pliocene monzogranitic rocks. The restricted access area delimiting the wreckage area has been in force since 2012: this measure avoids the interferences related to recreational or professional activities (e.g., diving, boating, fishing) during wreck removal and environmental restoration operations, and reduces human-related disturbance for the recovery of benthic ecosystems. To accelerate the recovery of the coralligenous assemblages at the Imp site, restoration activities have been undertaken since 2018. These involve transplanting *E. cavolini* and *P. clavata* colonies obtained from by-catch of local artisanal fishermen or found

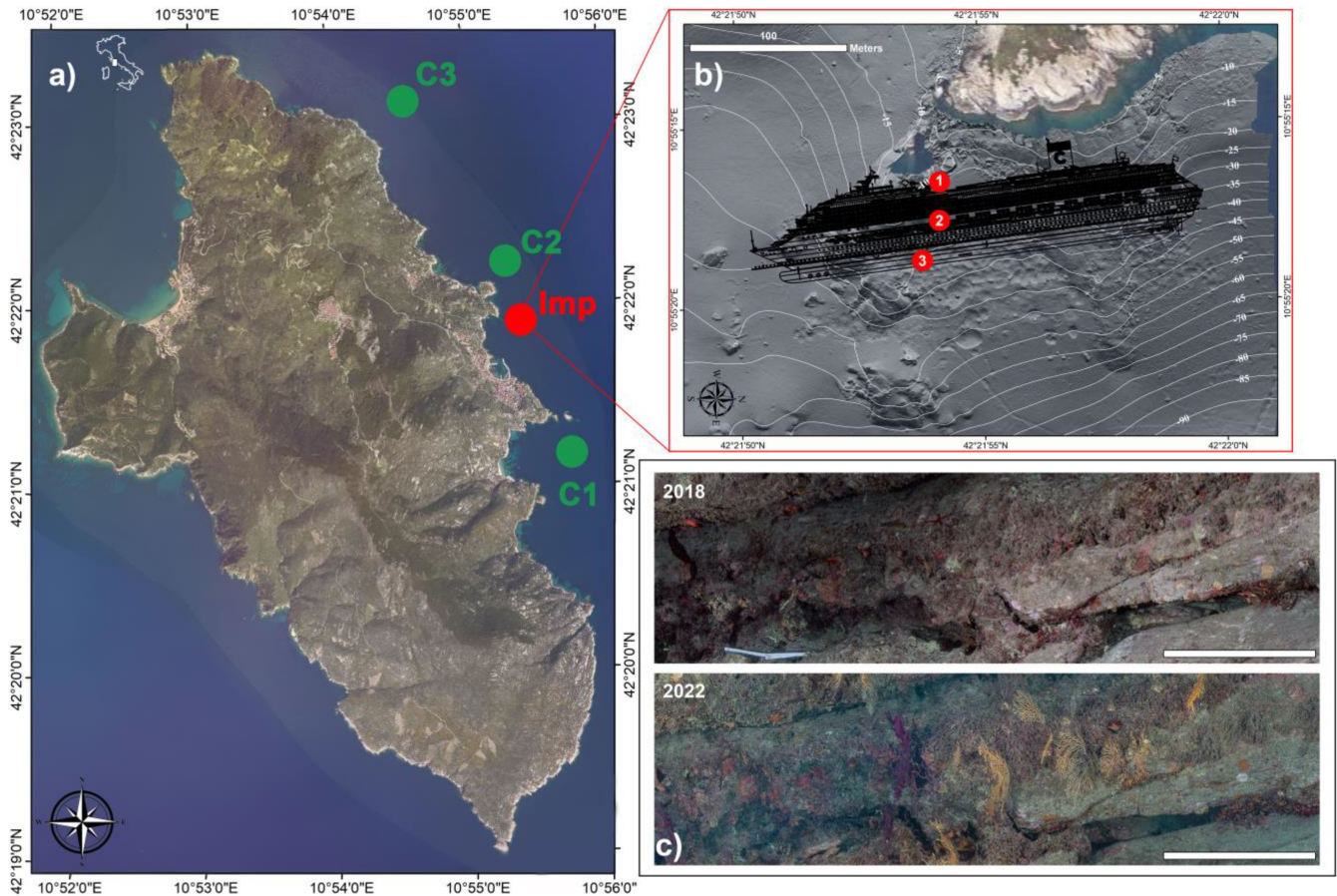


Figure 1. Maps of the study area and figures of the sampled reefs. The location of the four investigated sites, including the one within the wreckage-impacted area (Imp) and the three control sites (Le Sciole: C1; Punta del Lazzaretto: C2; Seccha della Croce: C3), is shown (A). The focus of the wreckage area includes morphobathymetric features of the seafloor, the outline of the wreck, and the position of the three stations (B): Station 1, Station 2, and Station 3. Portions of the photomosaic at Station 2 extracted in 2018 and 2022 (C). Scale bar 1 m.

naturally detached by SCUBA divers (Casoli et al. 2021a). The octocorals were transplanted using epoxy putty at depths between 20 and 35 m.

At Imp, coralligenous cliffs at three stations distributed between 20 and 36 m depth (identified as Station 1, Station 2, and Station 3; Fig. 1; Table S1) were sampled annually from 2018 to 2022, 1 year after the conclusion of cleaning activities, in late Spring or early Summer. The recently developed photomosaic technique was used for monitoring recolonization processes (Casoli et al. 2021b). This sampling technique was chosen as it effectively examines large portions of the reefs while maintaining high detail. Furthermore, in the context of the study's objective, it enabled a more detailed assessment of the recolonization dynamics on the same portion of substrate compared to other sampling methods. Using QGIS software, fixed photoquadrats measuring 50×40 cm (0.2 m^2) were superimposed on each photomosaic. The number of fixed photoquadrats per station (8, 15, and 15, respectively, for Stations 1, 2, and 3) was selected to cover at least 30% of the substrate surface shown in the photomosaic (Table S1). The images relating to these fixed portions of reefs were extracted for each of the five sampling events.

At each of the control sites, 30 photoquadrats of 0.2 m^2 were haphazardly collected on coralligenous cliffs from 2018 to 2022, in late Spring or early Summer. Here, no photomosaic and fixed photoquadrats were used: 50×40 cm images were acquired randomly within the same portions (measuring circa 12 m^2) of coralligenous cliffs developing between 25 and 35 m of depth. At the control sites, the standard photoquadrat technique was chosen to better reflect the natural heterogeneity; furthermore, the decision to avoid using photomosaics and fixed quadrats methods was driven by the need to minimize potential errors in the analysis of shaded or distorted areas resulting from the stitching of multiple images. The difference in sampling methods likely introduces variability when comparing Imp site to controls, but this was not reported as significant in the assessment of the composition and structure of the coralligenous assemblages (Casoli et al. 2021b).

Recolonization Dynamics and Restoration of Impacted Reefs

Photomosaics at Imp enclosed 23.5 m^2 of coralligenous cliffs. Sessile organisms within the fixed photoquadrats were identified

to the lowest possible taxonomic level. For conspicuous organisms, species-level identification was achieved, while taxa that could not be distinguished through photographs were classified into taxonomic groups. To assess the composition and structure of the coralligenous assemblage during the five sampling events, polygons were manually outlined using the freehand editing tool in QGIS and then assigned by the user to a specific taxon or taxonomic group. The area covered by each taxon or taxonomic group was calculated in QGIS and then reported as percentage cover with respect to the area of the fixed photoquadrat. Similarly, the percentage cover of bare surfaces (i.e., portions of coralligenous concretion characterized by no biological coverage) was also calculated. To facilitate comprehension and graphical representation of patterns in recolonization dynamics, taxa were further grouped into morpho-functional categories based on organisms' taxonomy, generation time, and growth form (following Casoli et al. 2024) and their percentage cover was calculated.

In addition, the transplanted species (*E. cavolini* and *P. clavata*) were analyzed to describe and monitor the restoration efforts. The survival rate (i.e., the ratio between the number of living and attached colonies and the total number of colonies transplanted), mean density values (number of colonies/m²), and the mean percentage cover at the monitored stations were also reported.

Comparison with Control Sites and Recovery Assessment

Thirty photoquadrats of 0.2 m² were analyzed per site within the depth range of 25–36 m in each sampling event to compare impacted and control sites. The images acquired at stations 2 and 3 of the Imp site were selected for the comparison, as they were within the previously defined depth range. To obtain a detailed understanding of the heterogeneity of both ecological and aesthetic metrics of natural assemblages, we decided not to aggregate the values from the control sites.

Presence and percentage cover were assessed for the 45 taxa/morphological groups proposed in the Ecological Status of Coralligenous Assemblages (ESCA index; Piazzini et al. 2017; Gennaro et al. 2020). We quantified α -diversity and β -diversity (at site level) as ecological metrics to characterize the features of the assemblages and assess the outcome of restoration intervention. α -diversity was defined as the mean number of taxa/morphological groups identified in the photographic samples. β -diversity was partitioned into the two components of nestedness (β_{NE}) and turnover (β_{TU}) to determine the respective contributions of these two distinct mechanisms in shaping the composition of communities in space and time (Baselga 2010, 2012). Nestedness refers to changes in the number of species due to gain or loss, with less diverse assemblages containing strict subsets of the species found in more diverse ones; turnover indicates the replacement of species, occurring when the loss of some species is balanced by the gain of new elements that compose the community. The compositional β -diversity was measured using the Jaccard dissimilarity index at the site level between consecutive sampling events, measuring the nestedness and turnover components of temporal change and the sum of both values

(i.e., the overall compositional β -diversity expressed as β_{JA}) by using the “beta.temp” function of the R package *betapart* version 1.6 (Baselga et al. 2018).

The aesthetic value of the investigated coralligenous reefs was estimated using the predictive model provided by Langlois et al. (2021). They trained a convolutional neural networks (CNN) algorithm, ResNet50, initialized with weights pre-trained on the ImageNet dataset (Deng et al. 2010), to predict aesthetic values of photographic quadrats obtained from a previous online survey available to the public (Tribot et al. 2016). The performance of the deep algorithm was enough to predict the aesthetic values of new coralligenous photographic quadrats ($r^2 = 0.83$). Compared to the aforementioned study, the photoquadrats of 0.2 m² acquired at the impacted and control sites were cropped to 40 × 40 cm, setting up a resolution of 500 × 500 pixels. Variations in brightness and color spectrum due to the acquisition of images over the sampling years were manually corrected in Photoshop®. The predictions of the aesthetic values were performed with Python 3.7, Pytorch 1.4.0, and torchvision 0.5.0.

Statistical Analysis

To test for differences in the percentage cover of bare surfaces, a two-way analysis of variance (ANOVA) was conducted with the station (three levels) and sampling events (i.e., years; five levels) as crossed fixed factors. The dependent variable was log-transformed ($\log[x + 1]$) to respect the ANOVA homoscedasticity assumption (Bartlett test, p -value = 0.629). Patterns in recolonization and structure of the assemblages at Imp were summarized using Principal Coordinates Analysis (PCoA): in the PCoA biplot, convex hulls were highlighted based on stations and sampling events. Then, permutational multivariate analysis of variance (PERMANOVA; Anderson 2001) and permutational analysis of multivariate dispersions (PERMDISP; Anderson 2006) were used to test differences in the structure of the assemblages at Imp according to stations and sampling events. Then, Tukey HSD post hoc tests were performed for pairwise multiple comparisons among factor levels that showed significant differences according to PERMDISP. These three analyses were based on a Bray–Curtis dissimilarity matrix calculated after log-transformation of the multivariate dataset with percentage cover of the benthic taxa.

Similarly, PCoA, PERMANOVA, and PERMDISP were carried out to show and test differences in the multivariate structure of the assemblages between conditions (fixed, two levels: impact and control sites) and sampling events. As for this comparison, the dissimilarity matrix was calculated using the Jaccard index, and PERMDISP was tested on the condition factor exclusively.

The univariate ecological and aesthetic metrics used to assess restoration actions' short-term effectiveness were tested using generalized linear models (GLMs) with both Poisson and Gaussian distributions. We considered α -diversity (i.e., the number of taxa/morphological groups found in photographic samples), the overall β -diversity (β_{JA}), and the aesthetic value of the monitored coralligenous reefs as response variables and

tested the effect of two predictors (condition and sampling event) and their interaction.

For all the aforementioned analyses, a significance level of 0.05 (p -value < 0.05) was selected. The statistical analyses were performed in the R platform (version 4.4.1).

Results

Coralligenous Reefs Recolonization and Restoration at Impacted Site

Overall, 27 species/taxonomic groups, belonging to 9 morpho-functional categories, were identified by analyzing photomosaics of impacted reefs (Table 1).

After cleaning operations, the percentage cover of bare surfaces was high at the three monitored stations (mean values \pm SD of 63.8% \pm 17.2% Station 1, 67.1% \pm 11.0% Station 2, and 53.9% \pm 28.8% Station 3). Afterward, it rapidly decreased in 2019 and then remained relatively stable, although variable among the fixed photoquadrats, through the final sampling event in 2022 (22.5% \pm 23.9% Station 1, 14.1 \pm 9.9% Station 2, and 27.2% \pm 23.7% Station 3; Fig. 2A). The station showing the significantly higher percentage cover of bare surfaces changed with sampling time (Table S2). The three stations shared the observed increase in species/taxonomic groups from 2018 to 2022 (from 10 to 15 in Station 1, from 15 to 19 both in Station 2 and Station 3) and corroborated the recolonization pattern (Fig. 2B). The structure of the assemblages showed a clear-cut separation among stations, while temporal patterns (among sampling events) were less evident. The distribution of data from the three stations revealed their location along the depth gradient: the convex-hull of Station 2 partially overlapped with those of Station 1 and Station 3, which were well separated (Fig. 3A). Conversely, differences between sampling events were not depicted, though the position of the observations on the PCoA plane reflected a gradual trajectory of change in the assemblages over time (Fig. 3B). The structure of the coralligenous assemblages at site Imp changed for the three stations differently across sampling events (PERMANOVA; Table S3). Significant differences in dispersion patterns for both the considered factors were observed through PERMDISP (Table S3). Specifically, the stations exhibited significant variation in their dispersion pattern, while significant differences in multiple pairwise comparisons were only found when comparing the assemblage structure from 2018 to that of other years.

The coverage percentages of the 27 species/taxonomic groups and 9 morpho-functional groups are reported in Table 1 and Figure S2, respectively. The recolonization patterns of impacted reefs were primarily driven by algal taxa, which exhibited the highest coverage values. Perennial algal encrusting taxa showed the most consistent increase by far. Seasonal algal turf did not exhibit a clear pattern over the sampling events, particularly in the deeper station, characterized by inter-annual fluctuations. In contrast, perennial algal turf increased with depth over time. Perennial algal erect taxa had the lowest coverage percentages among the algal categories. Regarding invertebrates, only taxa with encrusting and erect morphologies

displayed mean coverage values exceeding 5%. Animal encrusting organisms colonized the deeper reef of Station 3 to a greater degree. Conversely, taxa with an erect growth form exhibited a common increase across all three stations over the sampling period. The increase in coverage of erect invertebrates was due to two distinct processes: the natural recolonization by erect bryozoans during the years immediately following the cleaning activities, and the transplantation efforts of the species *E. cavolini* and *P. clavata* on the coralligenous reefs.

As for restoration efforts in the whole wreckage area, a total of 380 colonies were transplanted. Transplantations were carried out from 2018 to 2022 during the summer seasons, with a survival rate of 73.5% recorded in 2022 (Fig. S3). On the monitored reefs, both density and mean coverage similarly increased over time, reaching the highest mean values of 2.4 colonies/m² and 3.9% of cover for *E. cavolini*, and 1.1 colonies/m² and 6.6% of cover for *P. clavata* in 2022. No natural recruitment events were observed on the monitored impacted reefs.

Assessing the Short-Term Effects of Restoration Actions

The composition of coralligenous assemblages changed for each condition differently across sampling events (Table S4). Observations and the convex-hull highlighting C and Imp conditions were clearly separated on the PCoA plane (Fig. 4). Dispersion patterns did not differ significantly across the condition factor (PERMDISP p -value > 0.01).

The univariate ecological metrics (α -diversity and β -diversity) confirmed the differences between conditions (Table S5). Over time, the mean number of taxa/taxonomic groups increased at the Imp site (from 5 \pm 2 in 2018 to 9 \pm 2 in 2022), although the values remained considerably lower than those characterizing sites C (from 12 \pm 1 in 2018 to 14 \pm 1 in 2022; Fig. 5A). Accordingly, the compositional overall β -diversity (β_{JA}) showed a slightly increasing trend at site Imp, while exhibiting variation between years at sites C (Fig. 5B). Mean β_{JA} was considerably lower at site Imp (0.31 \pm 0.16) compared to sites C (C1: 0.50 \pm 0.11; C2: 0.53 \pm 0.13; C3: 0.48 \pm 0.12). The nestedness (β_{NE}) and turnover (β_{TU}) components of temporal change differed between conditions (Fig. 5C). At sites C, β_{TU} was the primary driver of β -diversity. On the contrary, β_{NE} characterized the earliest recolonization phase at site Imp, whereas β_{TU} gradually increased in the following sampling events.

At site Imp, the mean aesthetic value increased over time from 1,469.82 \pm 97.62 in 2018 to 1,584.50 \pm 107.28 in 2022 (Fig. 5D). Since 2020, no substantial differences in the mean aesthetic value of coralligenous reefs have been observed based on condition. Site C exhibited interannual oscillations, making clear temporal trends less evident; marked aesthetic score variation was evident for sites C2 and C3. All the intercepts of GLMs were deemed significant and were defined by condition C and the sampling event of 2018 (Table S5). The ecological and aesthetic univariate metrics were significantly lower for the condition Imp. The interaction effect between condition and sampling events revealed a significant increase for both α -diversity and aesthetic value, but not for the mean β -diversity value.

Table 1. List and mean percentage cover values of the 27 taxa/taxonomic groups and corresponding morpho-functional categories identified in the three stations for each sampling event. The detailed description of morpho-functional categories is provided in Figure S2 caption. The Gain/Loss column indicates the difference in percentage cover between the beginning and end of the study (2022–2018), with the size of the bar proportional to this value. Bars are shown only for those taxa/taxonomic groups that reported a difference ≥ 0.1 ; positive differences are highlighted in green, while negative values are highlighted in red. Weaker differences (<0.1) are highlighted with an asterisk.

Species	Morpho-functional categories	Station	2018	2019	2020	2021	2022	Gain / Loss between the 2018–2022 time interval
Algal turf	Seasonal algal turf	Station 1	8.18	17.97	22.10	17.65	24.37	
		Station 2	0.62	8.35	4.64	6.09	5.68	
		Station 3	9.19	9.66	25.38	11.32	5.53	
<i>Pseudochlorodesmis furcellata</i> (Zanardini) Børgesen, 1925	Perennial algal turf	Station 1	0.00	1.37	1.62	1.81	1.60	
		Station 2	0.75	6.97	7.46	4.94	13.57	
		Station 3	4.71	17.78	12.94	14.89	17.63	
Encrusting calcareous Rhodophyta (<i>Corallinales</i>)	Perennial algal encrusting	Station 1	2.64	3.08	8.42	9.67	8.48	
		Station 2	10.45	24.84	19.83	19.38	13.22	
		Station 3	24.58	22.36	23.62	29.24	29.65	
<i>Palmophyllum crassum</i> (Naccari) Rabenhorst	Perennial algal encrusting	Station 1	2.40	4.22	5.09	2.11	3.20	
		Station 2	0.22	0.25	0.28	0.58	0.47	
		Station 3	0.02	0.04	0.00	0.00	0.04	*
<i>Peyssonnelia</i> spp.	Perennial algal encrusting	Station 1	20.87	20.83	32.12	39.01	30.01	
		Station 2	17.12	44.33	52.35	48.89	35.39	
<i>Zanardinia typus</i> (Nardo) P.C. Silva 2000	Perennial algal erect	Station 3	1.47	1.36	2.38	4.30	5.03	
		Station 1	0.00	0.00	0.00	0.00	1.26	
		Station 2	0.00	0.00	0.00	0.00	0.00	
<i>Acrosyphyton purpuriferum</i> (J.Agardh) G.Sjostedt 1926	Perennial algal erect	Station 3	0.00	0.00	0.00	0.00	0.00	
		Station 1	0.00	0.00	0.11	0.00	0.00	
		Station 2	0.00	0.00	0.02	0.00	4.99	
<i>Codium bursa</i> (Linnaeus) C. Agardh 1817	Perennial algal erect	Station 3	0.00	0.00	2.11	0.65	1.40	
		Station 1	0.00	0.00	0.00	0.00	0.10	
		Station 2	0.00	0.00	0.00	0.00	0.00	
<i>Flabellia petiolata</i> (Turra) Nizamuddin 1987	Perennial algal erect	Station 3	0.00	0.00	0.00	0.00	0.00	
		Station 1	0.00	0.56	0.48	0.00	0.14	
		Station 2	0.00	0.00	0.01	0.01	0.02	*
<i>Halimeda tuna</i> (J.Ellis & Solander) J.V.Lamouroux 1816	Perennial algal erect	Station 3	0.00	0.00	0.00	0.00	0.01	*
		Station 1	0.00	0.00	0.06	0.00	0.00	
		Station 2	0.00	0.00	0.00	0.00	0.00	
<i>Padina pavonica</i> (Linnaeus) Thivy 1960	Perennial algal erect	Station 3	0.11	0.12	0.05	0.11	0.00	
		Station 1	0.00	0.00	0.12	0.43	0.37	
		Station 2	0.00	0.00	0.00	0.00	0.00	
<i>Cliona viridis</i> (Schmidt, 1862)	Perennial animal boring	Station 3	0.00	0.00	0.00	0.00	0.00	
		Station 1	0.00	0.00	0.00	0.00	0.00	
		Station 2	0.00	0.00	0.00	0.14	0.14	
<i>Leptosammia pruvoti</i> Lacaze-Duthiers, 1897	Perennial animal cup	Station 3	0.00	0.00	0.00	0.00	0.00	
		Station 1	0.00	0.00	0.00	0.00	0.00	
		Station 2	0.10	0.37	0.23	0.23	0.25	
Encrusting bryozoans	Perennial animal encrusting	Station 3	0.03	0.00	0.00	0.00	0.02	*
		Station 1	0.52	0.20	0.25	0.50	0.54	

Table 1. Continued

Species	Morpho-functional categories	Station	2018	2019	2020	2021	2022	Gain / Loss between the 2018-2022 time interval
<i>Spirastrella cunctatrix</i> Schmidt, 1868		Station 2	0.31	0.26	0.22	0.29	0.17	-
		Station 3	1.16	1.85	1.55	1.44	1.11	*
		Station 1	0.00	0.15	0.35	0.47	0.50	█
<i>Phorbas tenacior</i> (Topsent, 1925)		Station 2	0.37	0.65	0.80	0.36	0.35	█
		Station 3	0.10	0.11	0.41	0.19	0.23	█
		Station 1	0.00	0.00	0.00	0.00	0.00	*
<i>Serpulidae</i>		Station 2	0.00	0.04	0.01	0.01	0.03	*
		Station 3	0.00	0.00	0.00	0.00	0.00	█
		Station 1	0.21	0.30	0.21	0.26	0.53	█
<i>Halocynthia papillosa</i> (Linnaeus, 1767)	Perennial animal massive	Station 2	1.60	0.23	0.55	0.36	0.56	█
		Station 3	3.04	6.41	4.74	2.86	2.50	█
		Station 1	0.00	0.00	0.00	0.01	0.01	*
<i>Hemimycale columella</i> (Bowerbank, 1874)		Station 2	0.50	0.62	1.09	1.19	1.29	█
		Station 3	0.01	0.83	1.32	1.34	1.36	█
		Station 1	0.00	0.00	0.00	0.00	0.00	█
<i>Axinella polypoides</i> Schmidt, 1862	Perennial animal tree	Station 2	0.00	0.00	0.00	0.00	0.00	█
		Station 3	0.16	0.97	1.08	0.00	0.00	-
		Station 1	0.00	0.00	0.00	0.00	0.00	█
<i>Eudendrium</i> spp.		Station 2	0.00	0.00	0.00	0.00	0.00	█
		Station 3	0.00	0.00	0.00	0.73	0.73	█
		Station 1	0.00	0.00	0.00	0.00	0.00	-
<i>Eunicella cavolini</i> (Koch, 1887)		Station 2	0.12	0.00	0.00	0.39	0.00	█
		Station 3	0.00	0.00	0.00	0.08	0.08	█
		Station 1	0.18	1.76	1.84	1.98	3.93	█
<i>Myriapora truncata</i> (Pallas, 1766)		Station 2	0.00	0.43	0.43	2.76	2.32	█
		Station 3	0.00	0.00	0.00	0.23	0.24	█
		Station 1	0.00	0.01	0.00	0.00	0.00	█
<i>Paramuricea clavata</i> (Risso, 1827)		Station 2	0.00	0.00	0.00	0.00	0.00	*
		Station 3	0.00	0.00	0.00	0.00	0.00	█
		Station 1	0.00	0.00	0.00	0.00	0.00	█
<i>Reteporella</i> spp.		Station 2	0.00	2.26	3.80	6.74	6.66	█
		Station 3	0.00	0.00	0.30	4.75	6.15	█
		Station 1	1.13	4.08	2.78	1.37	2.01	█
<i>Sabellidae</i>		Station 2	0.61	0.89	0.17	0.33	0.60	█
		Station 3	0.65	0.74	0.04	0.16	0.79	█
		Station 1	0.02	0.08	0.00	0.00	0.00	█
<i>Smitina cervicornis</i> (Pallas, 1766)		Station 2	0.11	0.33	0.53	0.30	0.17	█
		Station 3	0.65	2.96	0.35	0.23	0.22	█
		Station 1	0.03	0.19	0.38	1.09	0.40	█
		Station 2	0.06	0.10	0.08	0.01	0.06	█
		Station 3	0.16	0.17	0.06	0.03	0.07	*

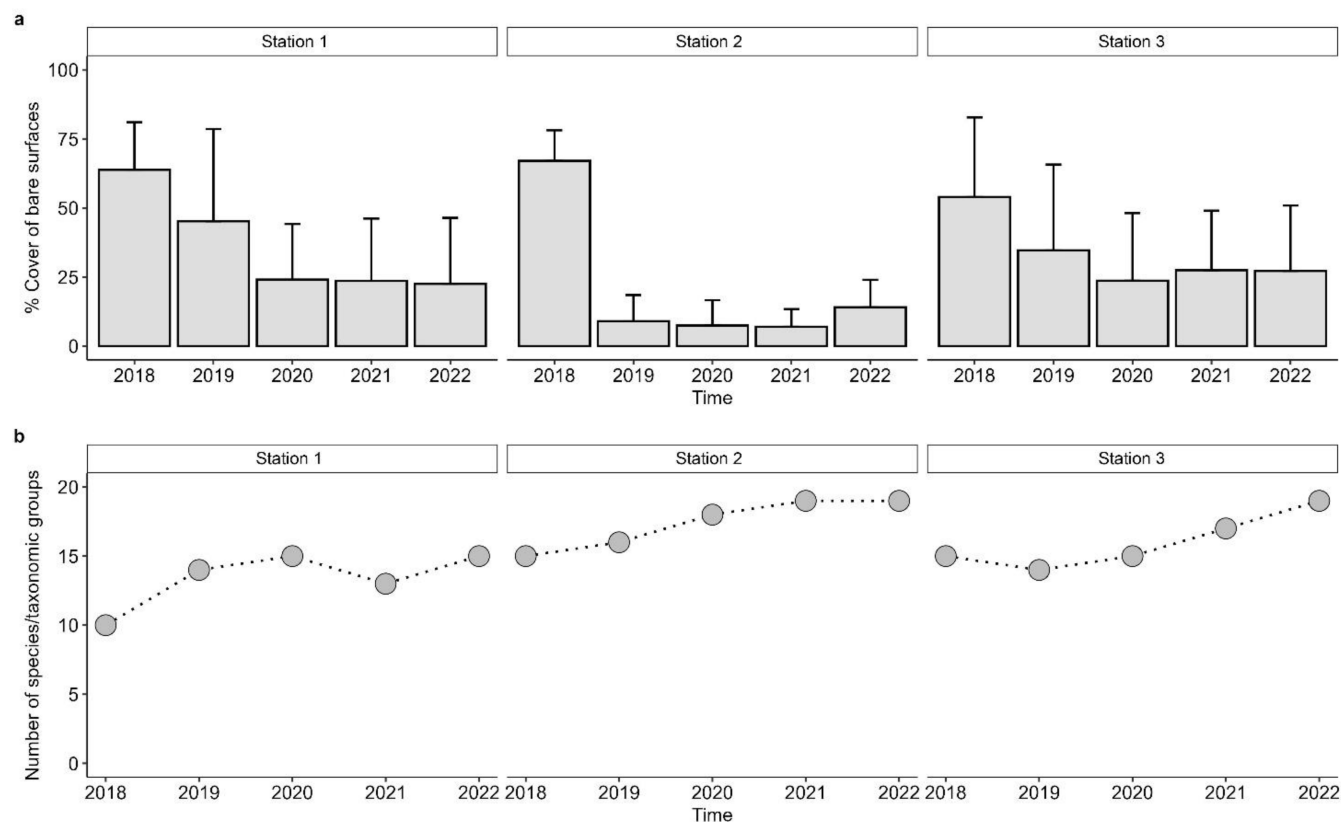


Figure 2. (A) Mean percentage of cover of bare surface (\pm SD) and (B) total number of species/taxonomic groups identified across sampling events at each station monitored at site Imp.

Discussion

The present study quantifies the short-term effects of both passive (i.e., protection measures) and active restoration (i.e., removal of disturbances and transplants of structuring species) on the coralligenous reefs impacted by the Costa Concordia shipwreck. This case study represents the first attempt to assess multiple ecosystem features, including community structure, diversity patterns, and aesthetic value, the last one indicating people's perception of CES. The results showed that the full recovery of coralligenous reefs is slow and unrealistic in the short term. After 5-year monitoring, significant differences in community diversity patterns persist between impacted and control sites. However, the steady increase of the investigated metrics, particularly the aesthetic value of the reefs, indicates that the coupled effect of passive and active restoration aids in recovering the ecological processes of impacted coralligenous reefs.

The seabed cleaning phase has opened a "recruitment window" on a calcareous bare substrate, thus enabling ecological succession to be re-established on the reefs. Many studies reported that substrates become fully colonized within 12 months (Antoniadou et al. 2010; Teixidó et al. 2013); however, it can be challenging to compare our data because previous estimates were performed on artificial substrates or not completely bare reefs. The community's recovery was exclusively supported by larval settlement and encroachment from above concretion portions, due to the lack of surviving biotic

patches on the reefs after the cleaning phase. The low dynamics of coralligenous species and the infrequent recruitment events of some clonal organisms and populations, as suggested by some authors (Teixidó et al. 2011; Montero-Serra et al. 2018), may have contributed to the slow observed recovery.

At the impacted site, the community structure remained stable, without exhibiting significant phase shifts, and reflected the characteristics typical of the early stages of community development. The results of this study align with the conceptual model of recruitment processes proposed for coralligenous outcrops in the northern Adriatic Sea (Fava et al. 2016). Although the sampling design adopted here does not allow a focus on the earliest stages of recolonization (i.e., the first months following seafloor cleaning), the pioneer species (e.g., serpulids and encrusting bryozoans), known for their high reproductive potential and fast growth (Cotter et al. 2003; Sokolover et al. 2018), were gradually replaced by organisms that constitute the basal layer of coralligenous communities and contribute, in part, to the bioconstruction process. The recolonization process is primarily driven by local species present on surrounding healthy coralligenous reefs. Encrusting coralline algae contribute to reef growth by depositing calcium carbonate and promote the settlement of benthic invertebrates, with the associated microbial biofilms (Huggett et al. 2018). Erect bryozoans and ascidians characterized the initial phases of recolonization, similarly to what has been reported in deeper coralligenous reefs (Casoli et al. 2020). As the sole suspended feeders naturally settled

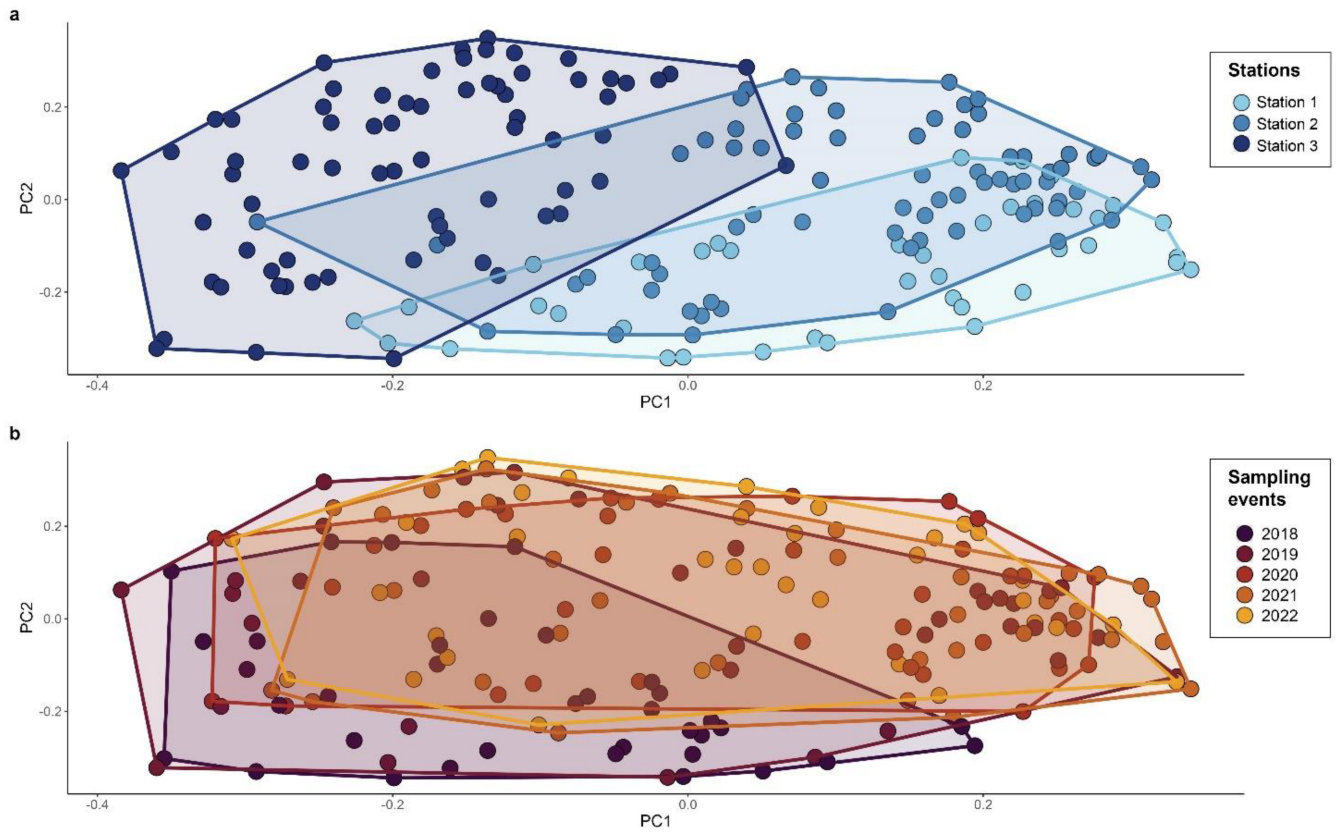


Figure 3. PCoA bi-plots comparing the structure of the assemblages at site Imp according to monitored stations (A) and sampling events (B): dots indicate fixed photoquadrats. The two displayed axes explained 51.36% of the total variance.

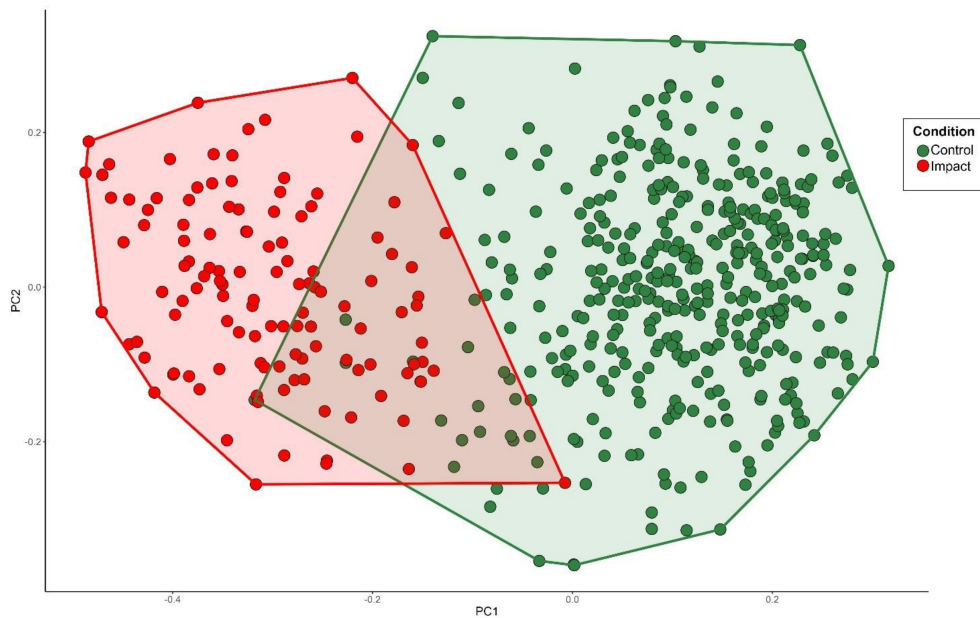


Figure 4. PCoA bi-plot depicting the structure of coralligenous assemblages based on Jaccard similarity according to condition: Impact (site Imp) and control/natural (site C1, C2, and C3 considered together). Dots indicate photoquadrats. The two displayed axes explained 33.71% of the total variance.

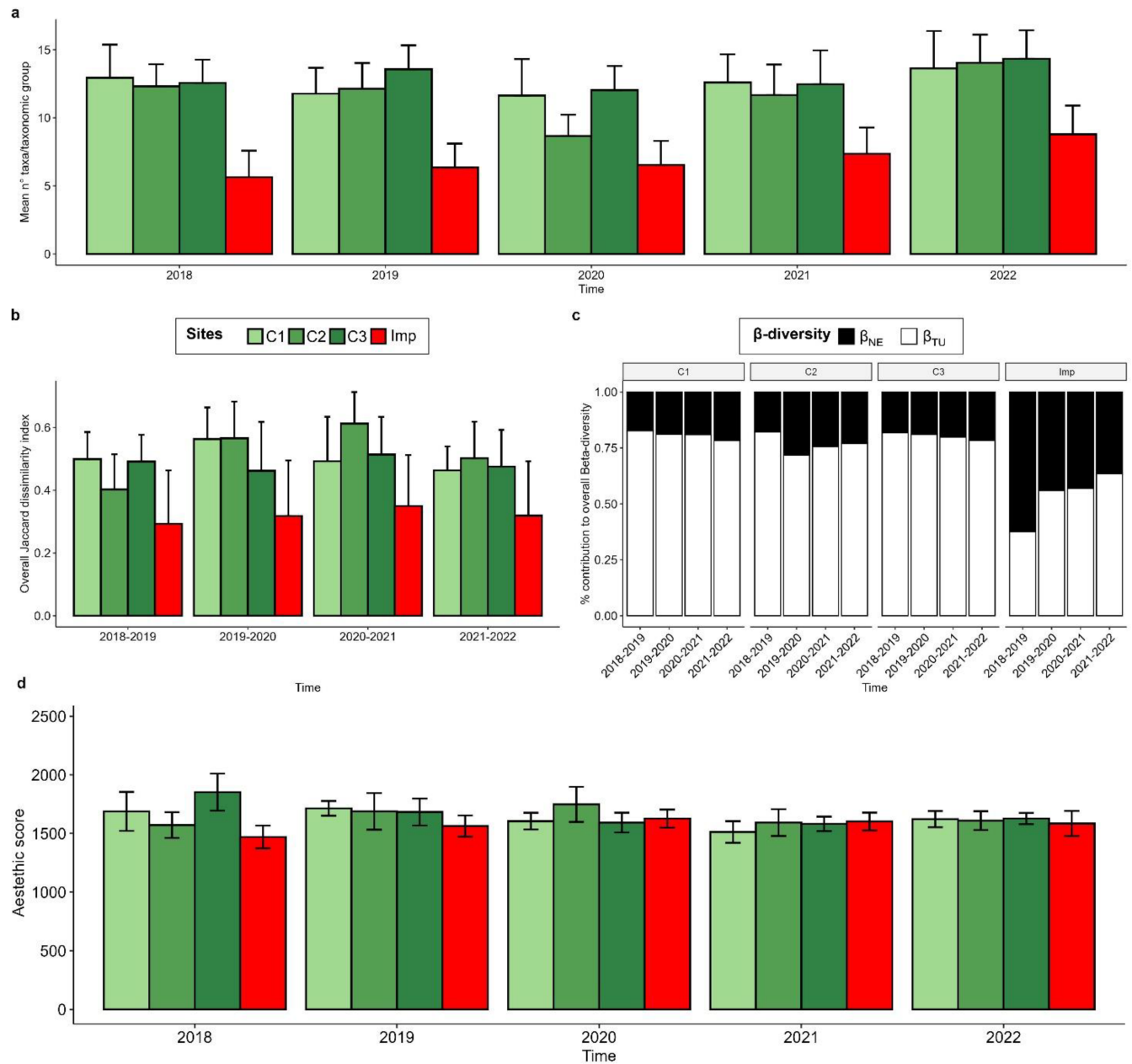


Figure 5. The univariate ecological metrics at the monitoring sites. α -diversity, measured as the mean number of taxa/taxonomic groups counted in photoquadrats, in the five sampling events (A). Temporal pattern of overall compositional β -diversity (β_{JA}), measured using the Jaccard dissimilarity index at the site level between consecutive sampling events (B). Mean percentage contribution of nestedness (β_{NE}) and turnover (β_{TU}) components of β -diversity at the monitoring sites (C). The aesthetic value of the coralligenous reefs at the four monitored sites (D). Error bars indicate \pm SD.

on the bare surfaces, these taxa may play a key role in the functioning of reefs through benthic-pelagic coupling.

Depth and proximity to the wreck, which has been a major source of disturbance, drive the observed differences in community structure across the three stations. The increase in heterogeneity of sampling units over time may indicate that very small-scale factors (e.g., recruitment events, growth) contributed to divergent development trajectories among the sampling quadrats. Such an increasing pattern is consistent with the high variability reported at small spatial scales for mature assemblages at

low-impact sites (Piazzi et al. 2016). However, the gradual change at the impacted reefs did not affect the domains of stability in this early stage (Beisner et al. 2003). We can argue that transplants did not significantly alter the dynamics of the community; these efforts allowed the introduction of gorgonian species that had colonized the reefs before the wreckage, but did not naturally settle on the impacted reefs once the recolonization processes began. Such evidence contrasts with observations of some authors who reported an increase in coral recruitment rates following catastrophic disturbances (Bramanti & Edmunds 2016;

Ruffaldi Santori et al. 2021). The high survival rates of transplanted colonies, associated with sporadic settlement events of *E. cavolini* and *E. singularis* colonies observed by the authors on concretions deeper than 60 m and gently sloping granite rock respectively (authors personal observations), and the distance of natural populations (approximately 200 m away), could contribute to the establishment of stable local populations in the future.

The impacted reefs differ when compared to control reefs, both in community composition and the ecological metrics. α - and β -diversity prove to be effective synthetic descriptors not only for assessing the impact condition of coralligenous reefs (Piazzini et al. 2021) but also for tracking their gradual recovery. The average number of taxa/taxonomic groups for the two conditions aligns with those reported from coralligenous reefs in the Tyrrhenian basin (Piazzini et al. 2019, 2023). With this regard, the value recorded in 2018 at the impacted site is considerably lower than in sites subject to chronic disturbance (Piazzini et al. 2019), highlighting how sporadic and high-magnitude disturbance can have long-term consequences on the ecological state of the community.

The results showed an overall increase in β -diversity at the impacted site, indicating that the community composition changed over time. On the contrary, control sites report values that fluctuate over the years while remaining consistently high. The partitioning of β -diversity highlights how the contributions of nestedness and turnover vary across conditions. The compositional dissimilarity of communities in control sites is primarily driven by species turnover. This finding contrasts with the slow temporal dynamics described for coralligenous habitats by some authors (Teixidó et al. 2011) and may be attributed to interannual differences in the development of seasonal species (e.g., turf algae) or to the sampling methodology. Given the small-scale spatial heterogeneity of these communities, the haphazard acquisition of images within reefs could maintain these differences high within the same site across different years (Casas-Güell et al. 2015). Turnover phenomena shape community composition on impacted reefs over time. The slow-growing species of coralligenous reefs can coexist with pioneer species during early development (Garrabou et al. 2002), resulting in a higher nestedness component. Subsequently, the growth of highly competitive species, along with octocorals transplantation activities, promotes species substitution as a driver of community dynamics. In particular, octocorals transplantation will likely impact the future dynamics of the reefs: the survival and growth of the transplanted colonies may restrict other organisms from colonizing the same areas of the substrate.

Interestingly, the aesthetic value of impacted reefs contrasted with ecological metrics, showing a rapid recovery that matched the control sites by 2020. Langlois et al. (2021) highlighted that human aesthetic preferences do not always align with coralligenous reefs' ecological status and taxonomic diversity. Such an aesthetic bias in human perception is confirmed in the present study: the presence and increasing relative abundance of species that positively contribute to aesthetic value in the initial stage of reef recolonization, such as bryozoans (both encrusting and erect forms) and transplanted octocorals, may explain the observed pattern. They create distinguishable patches against the background that are highly valued (Chatterjee & Vartanian 2014). Such a

feature was more prevalent in reefs with uncolonized areas and patches of recently settled or transplanted organisms.

This study highlights the importance of active restoration in recovering the ecological processes of impacted coralligenous reefs. The results align with observations in other Mediterranean coastal ecosystems (Bacci et al. 2024; Galobart et al. 2024; Zentner et al. 2025), underscoring the need for a much longer timeframe than that covered by the monitoring period to fully recover the ecosystem's structure and processes. The combination of restoration and long-term protection efforts ensures the achievement of persistent conservation objectives (Possingham et al. 2015). The use of synthetic metrics allows overcoming the approaches based solely on the attributes of the transplanted species: they account for the recovery of community structure, evaluate ecological processes (e.g., recruitment and dynamics), and assess CES. Furthermore, the use of descriptors such as α and β -diversity enhances the comparability of the results with studies conducted on coralligenous reefs (Piazzini et al. 2021), allowing for a more precise delineation of recovery trajectories through the use of multiple natural reference sites. This may have implications for defining the success criteria of restoration efforts, as highlighted by Frascchetti et al. (2021).

Seabed cleaning operations enable a slow and gradual recovery of community diversity; transplantations allow for the presence of adult colonies of the transplanted species, for which no natural settlement events were observed. Although the densities achieved through transplantation may not have influenced the settlement processes of sessile organisms, the presence of transplanted colonies may have contributed to the rapid recovery of the aesthetic value of the impacted coral reefs. The variability of ecological succession processes might lead the communities at impacted sites toward equilibrium states that diverge from their original condition or differ from those in control sites (Santangelo et al. 2015). This aspect raises fundamental questions for future evaluations of restoration interventions, especially when accurate *pre*-impact information is lacking, and the success of restoration is assessed through comparisons with control sites. In such cases, can a target-oriented approach, focused on ecosystem functions rather than the reassembly of species and communities, be favored over less realistic reference-oriented approaches (Choi 2007)?

Defining priority target ecosystem services is gradually influencing the approach of ecological restoration interventions (Carlucci et al. 2020). However, the assessment of the effects of ecological restoration on CES remains largely underexplored, particularly in the Mediterranean Sea. The quantification of aesthetic value plays a crucial role within this framework, as it influences public perception and appreciation of the implemented interventions. While this may conflict with conservation needs, engaging in underwater controlled activities or enjoying the restored seascape can provide benefits not only for human well-being but also for the sustainability of the interventions themselves. This, in turn, can enhance the perceived effectiveness of restoration efforts not only among managers and stakeholders but also among the public and end-users. The quantification of the aesthetic value of restored coralligenous reefs enables the assessment of the ability of restored reefs to maintain and enhance CES. Similar approaches, capable of quantifying non-material

benefits, should be integrated into future designations and evaluations of restoration interventions or, more broadly, into conservation strategies favoring the recovery of status, functions, and processes of benthic ecosystems.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Photo-table illustration.

Figure S2. The structure of the coralligenous assemblages at the site Imp.

Figure S3. Monitoring the restoration of *E. cavolini* and *P. clavata* population at Imp site.

Table S1. Information on the three stations at site Imp.

Table S2. Two-way ANOVA results of the effects of the station, sampling event, and their interaction.

Table S3. Results of the PERMANOVA, PERMDISP, and Tukey HSD post hoc test.

Table S4. Results of the PERMANOVA and PERMDISP.

Table S5. Results of the GLMs with both Poisson and Gaussian distribution.

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