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Involving fishers in scaling up the restoration of cold-water coral gardens on the Mediterranean continental shelf.

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Abstract:	Cold-water gorgonians dwelling on the continental shelf are a common by-catch of bottom-contact fishing practices. Given the slow growth and limited recruitment of cold-water gorgonians, impacts derived from fishing activities may seriously compromise the conservation of the highly complex coral gardens which they generate, as well as the abundant and highly diverse associated fauna. For this reason, the development of effective active and passive restoration methods is nowadays a priority to enhance the natural recovery of impacted cold-water coral gardens. However, ecological restoration of mesophotic and deep-sea communities remains extremely limited, due to their technological requirements and associated costs bringing their wide-scale and long-term application into question. This study reports the results of the first large-scale active restoration of more than 400 cold-water gorgonians on the Mediterranean continental shelf. By actively involving local fishers during two consecutive fishing seasons, by-catch gorgonians were recovered and returned to the continental shelf (at 80–90 m depth). Two-years monitoring performed through Autonomous Underwater Vehicle (AUV) surveys revealed that 460 gorgonian transplants survived over an area of 0.23 ha. This reintroduced cold-water gorgonian population is compared to a reference natural population in terms of size and spatial structure. The cost of the restoration amounted to 140 000 €/ha, which is significantly less than for any deep-sea restoration actions performed to date. The success of this cost-effective active

	restoration highlights the viability of large-scale restoration of impacted cold-water coral communities, with promising results for the conservation and recovery of mesophotic and deep-sea ecosystems.
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Dear Editor,

We are pleased to submit the enclosed manuscript entitled "Involving fishers in scaling up the restoration of cold-water coral gardens on the Mediterranean continental shelf" for consideration for publication in Biological Conservation.

General awareness of marine habitat degradation is steadily growing. Consequently, marine ecological restoration initiatives are receiving increasing attention, especially those focusing on benthic engineer species such as corals in shallow tropical habitats. However, the need to preserve and restore mesophotic and deep-sea environments has become increasingly evident due to cumulative human impacts, as most benthic communities at these depths have been seriously degraded by commercial fishing activities. To date, only a few ecological restoration actions have been carried out at intermediate depths and in deep-sea habitats at local scales, due to technical and economic limitations which questions its application efficiency.

The aim of our study is to explore, for the first time, the possibility of scaling up restoration actions at deep environments through the application of a cost-effective restoration method working in close collaboration with local fishers. The restoration project performed during two consecutive years was aimed at restoring gorgonian gardens on the Mediterranean continental shelf collecting by-catch gorgonians obtained from artisanal fishing, and returning them to their natural environment on the continental shelf. Gorgonians are among the main structuring species of benthic communities on the continental shelf and slope, and they play a paramount ecological role in mesophotic and deep-sea ecosystems. Due to their morphology (erect and branched), gorgonians are frequently entangled in fishing nets, and their ecological characteristics (long-lived and slow growing species with low recruitment success) compromise the recovery and long-term viability of impacted populations. Our study demonstrates that a large number of gorgonians (460 colonies) were successfully reintroduced and survived after two-years at 80-100 m depth. The results suggested an initial establishment of a new gorgonian population, which will potentially evolve toward a comparable natural population in terms of size and spatial structure, if natural recruitment occurs. This study confirms the viability of a large-scale and cost-effective restoration method aimed at enhancing the recovery of impacted cold-water coral gardens.

We confirm that this manuscript is all original research, has not been published elsewhere, and is not under consideration by any other journal. All the authors agree with submission to Biological Conservation. All sources of funding are acknowledged in the manuscript. We have no conflicts of interest to declare.

Thank you for your consideration of our manuscript. We look forward to hearing from you.

Yours sincerely,

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Highlights

- Gorgonians were recovered from by-catch and returned to the continental shelf.
- Photomosaic surveys showed the establishment of a reintroduced gorgonian population.
- By involving local fishers, the low-tech restoration method resulted in low-cost.
- The method allows for wide-scale application.

Abstract

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Involving fishers in scaling up the restoration of cold-water coral gardens on the Mediterranean continental shelf

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Abstract

Cold-water gorgonians dwelling on the continental shelf are a common by-catch of bottom-contact fishing practices. Given the slow growth and limited recruitment of cold-water gorgonians, impacts derived from fishing activities may seriously compromise the conservation of the highly complex coral gardens which they generate, as well as the abundant and highly diverse associated fauna. For this reason, the development of effective active and passive restoration methods is nowadays a priority to enhance the natural recovery of impacted cold-water coral gardens. However, ecological restoration of mesophotic and deep-sea communities remains extremely limited, due to their technological requirements and associated costs bringing their wide-scale and long-term application into question. This study reports the results of the first large-scale active restoration of more than 400 cold-water gorgonians on the Mediterranean continental shelf. By actively involving local fishers during two consecutive fishing seasons, by-catch gorgonians were recovered and returned to the continental shelf (at 80–90 m depth). Two-years monitoring performed through Autonomous Underwater Vehicle (AUV) surveys revealed that 460 gorgonian transplants survived over an area of 0.23 ha. This reintroduced cold-water gorgonian population is compared to a reference natural population in terms of size and spatial structure. The cost of the restoration amounted to 140 000 €/ha, which is significantly less than for any deep-sea restoration actions performed to date. The success of this cost-effective active restoration highlights the viability of large-scale restoration of impacted cold-water coral communities, with promising results for the conservation and recovery of mesophotic and deep-sea ecosystems.

1. Introduction

Anthropogenic impacts, which are increasing in terms of magnitude, scale, frequency, and diversity have disrupted ecosystem processes to a large extent and diminished over 60% of the ecosystem services, leading to a serious loss of biodiversity (Millenium Ecosystem Assessment, 2005; Jackson et al., 2001; Mooney et al., 2009). Focusing on the marine environment, the escalation of human activities (i.e., fishing, oil and gas extraction, mining) and climate change are seriously imperilling marine ecosystem's biodiversity, functioning, stability, and resilience (Dulvy et al., 2008; Hughes, 1994; Ramirez-Llodra et al., 2011). Anthropogenic impacts on the oceans show strong spatial heterogeneity and are mostly concentrated on continental shelf and slope areas (Halpern et al., 2008). In fact, half of the world's continental shelves are continuously being impacted by fishing activities, especially bottom trawling (Pusceddu et al., 2014; Watling and Norse, 1998). Fishing practices directly damage benthic fauna, mainly engineering species (sensu Jones et al., 1994) such as corals, gorgonians and sponges (Fosså et al., 2002; MacDonald et al., 1996; Reed, 2002). Bottom-contact fishing gears, such as trawling, longlines, gills and trammel nets, get easily entangled in benthic sessile fauna specially corals and gorgonians, directly breaking, tilting their colonies or scattering fragments (Gage et al., 2005; Martín et al., 2014; Mortensen and Buhl-Mortensen, 2005; Pham et al., 2014). Overall, cumulative effects result in fragmented and isolated populations, increasing their vulnerability to further disturbances (Hughes and Connell, 1999). Furthermore, the loss of key habitat-forming organisms results in the disappearance of suitable habitat for a significant number of associated species, representing a simplification of the structure and functioning of the entire benthic community (Althaus et al., 2009; Clark et al., 2010; Clark and Rowden, 2009; Thrush and Dayton, 2002).

Cold-water corals (CWC) are widely distributed in the world's oceans, mostly between 50 and 4000 m depth, playing crucial structural and functional role in mid-depth and deep-sea ecosystems (Orejas and Jiménez, 2019; Roberts et al., 2009, 2006). They form complex three-dimensional structures that act as shelter, feeding and nursery areas for a highly-diverse associated fauna, including species of high commercial interest (Henry and Roberts, 2007; Miller et al., 2012; Roberts and Hirshfield, 2004) while creating hotspots of biodiversity (Henry and Roberts, 2016; White et al., 2012). Moreover, these coral assemblages take an active part in most bio-geochemical cycles and benthic-pelagic coupling processes enhancing ecosystem functioning (Cathalot et al., 2015; Rovelli et al., 2015; Wild et al., 2009). CWC are slow-growing, high-longevity species, with delayed sexual maturity and infrequent recruitment success (Andrews et al., 2002; Brooke and Young, 2003; Orejas et al., 2011; Reed, 2002; Watling et al., 2011). As a consequence, CWC ecosystems are highly vulnerable to anthrophogenic impacts and display reduced recovery capacity, which can jeopardize their long-term viability (Huvenne et al., 2016; Williams et al., 2010). Specifically, several studies have demonstrated that recovery of CWC ecosystems after anthropogenic impacts could take decades to centuries, if recovery is possible at all (Althaus et al., 2009; Girard et al., 2018; Huvenne et al., 2016; Williams et al., 2010). Therefore, given their life traits and ecological significance and vulnerability, protection of CWC ecosystems has been stated as a major priority in marine management strategies (Armstrong et al., 2014). In recent years, CWC ecosystems have been recognized as Vulnerable Marine Ecosystems (FAO, 2009) and their conservation is now internationally recognized as a high priority for the maintenance of marine biodiversity (Thurber et al., 2014). Conventions, directives and policies (Christiansen, 2010; COM, 2008; Hall-Spencer and Stehfest, 2009; OSPAR Commission 2010; FAO, 2016) underline the importance of sustainably managing and protecting CWC ecosystems, addressing both the loss of biodiversity and ecosystem functioning (Armstrong et al., 2014; Bennecke and Metaxas, 2017; Otero and Marín, 2019).

In this context, ecological restoration assisting the recovery of impacted ecosystems represents a worldwide-recognized strategy to complement protection and management measures (Gann et al., 2019; McDonald et al., 2016). The effectiveness of a passive restoration approach, such as the implementation of deep-sea marine protected areas, has been evidenced by CWC re-growth, recruitment and recovery of associated megafauna abundance after years of protection (Baco et al., 2019; Bennecke and Metaxas, 2017; Harter et al., 2009). However, given the scale of accumulated impacts, protection may not always be sufficient (Huvenne et al., 2016) and additional active ecological restoration may be required to enhance the recovery of impacted habitats (Lotze et al., 2011; Rinkevich, 2005). In fact, active restoration actions have been widely developed for terrestrial (Harker, 1999; Lamb, 1998) and marine ecosystems (Duarte et al., 2020). Nonetheless, the vast majority of actions performed at sea have been heavily skewed toward shallow tropical (e.g., Epstein et al., 2001; Pizarro et al., 2014; Rinkevich, 2005) and temperate habitats (e.g. Layton et al., 2020; Linares et al., 2008; Verdura et al., 2018) whereas restoration actions focused on deeper habitats remain scarce (Morato et al., 2018; Van Dover et al., 2014). Despite awareness of the need to protect deep-sea environments, only few studies have addressed the active restoration of CWC habitats (Brooke et al., 2006; Dahl, 2013; Jonsson et al., 2015; Montseny et al., 2019), stressing that we are in an initial and pioneering developmental phase for restoration techniques suitable for CWC habitats. Recent studies have successfully evaluated transplantation techniques to restore CWC reef-forming species (Brooke et al., 2006; Dahl, 2013; Jonsson et al., 2015) and CWC garden ones (Boch et al., 2019; Montseny et al., 2019). The main challenges for CWC restoration are principally based on our vast lack of knowledge about biodiversity, functioning and resilience of deep-sea ecosystems (Da Ros et al., 2019; Morato et al., 2018; Van Dover et al., 2014). On the other hand, the difficult access to CWC habitats and major expenses related to the required technology, technically and economically limit the spatial scale of restoration actions. Local interventions are far from adequate to match the scale of ecosystem degradation (Bayraktarov et al., 2016; Boström-Einarsson et al., 2020) and scientific efforts are currently focusing on expanding the spatial scale of CWC active restoration actions, making them technologically and economically affordable (Aronson and Alexander, 2013; Da Ros et al., 2019; Perring et al., 2018). Integrating ecological data with economic and social aspects is becoming a crucial component in ecosystem management (Hull and Gobster, 2000; White et al., 2005). Cost information is essential for ecological restoration planning because it allows for selecting the best approaches (Iftekhar et al., 2017) and identifying aspects that need to be improved (Edwards et al., 2010). However, studies on restoration costs are still limited (Bayraktarov et al., 2016), with less than 5% of studies including an economic evaluation (De Groot et al., 2013; Wortley et al., 2013). To account for all types of costs associated with a restoration action is not an easy task (De Groot et al., 2013; Bayraktarov et al., 2016) due to the difficulties of standardizing cost analysis methods and outputs (Bullock et al., 2011; Spurgeon and Lindahl, 2000). Nonetheless, the few studies which have addressed the economic costs of deep-sea active ecological restoration actions have highlighted the fact that economic costs are two to three orders of magnitude higher than for shallow areas (Boch et al., 2019; Da Ros et al., 2019).

Given this situation, the present study aims to go one step further in the restoration of CWC gardens, by scaling up the restoration of gorgonian populations on the Mediterranean continental shelf applying a low-cost method (Montseny et al., 2020) and involving local fishers. The active participation of local actors and stakeholders in ecological restoration actions may play a decisive role in their successful development (Hull and Gobster, 2000; Yap, 2000). The restoration method consists of reintroducing by-catch gorgonians to their natural habitat by attaching them to cobble supports, and gently throwing them from the sea surface. A two-year restoration study to evaluate the ecological and socio-economic effectiveness has been carried out.

2. Material and methods

2.1 Target habitat and species

The restoration action was conducted on the continental shelf of the marine protected area of Cap de Creus (north-western Mediterranean Sea, 42° 19′ 12″ N - 03° 19′ 34″ E) (Figure 1). In this area, outcropping rocks and coarse-grained sediments support an extensive population of the gorgonian *Eunicella cavolini* (Koch, 1887) at 80–120 m depth (Gili et al., 2011; Lo Iacono et al., 2012). Gorgonians are patchily distributed, with spots dominated by medium to large sized colonies, reaching densities up to 20 colonies m^{-2} (Dominguez-Carrió, 2018; Dominguez-Carrió et al., 2014). *E. cavolini* is a common azooxanthellate Mediterranean gorgonian species occurring in a wide bathymetric distribution range (< 10–220 m depth) (Bo et al., 2012; Grinyó et al., 2016; Russo, 1985). Colonies usually display a fan-shaped morphology with a varied branching pattern, depending on environmental conditions, but mainly lying on a single plane oriented perpendicularly to the dominant current (Velimirov, 1973; Weinbauer and Velimirov, 1995). The size of *E. cavolini* colonies reported in the Mediterranean continental shelf is quite variable ranging from 9±7 to 15±10 cm in the Menorca Channel (Grinyó et al., 2016) and from 18±2 to 25±3.5 cm in the south Tyrrenian Sea (Bo et al., 2012). The largest colonies can reach 50 cm height (Bo et al., 2012; Grinyó et al., 2016). *E. cavolini* has slow growth rates (a few cm $year^{-1}$), and low recruitment success with lifespans around two decades (Sini et al., 2015; Weinbauer and Velimirov, 1995). Moreover, its populations hold a great diversity of associated species such as sponges, soft corals, bryozoans, hydrozoan, polychaetes and some species of high commercial interest such as spiny lobsters or scorpionfishes (Dominguez-Carrió et al., 2014). For this reason, artisanal fishing with trammel nets, longlines and traps are extended and permitted in the area. Due to their arborescent morphology, gorgonians are highly susceptible to being entangled by nets. As a consequence, colonies of *E. cavolini* are among the more accidentally caught species, which represents a significant threat to these populations (Dominguez-Carrió et al., 2014; Enrichetti et al., 2019).

2. 2 Restoration action

The restoration action was carried out in close collaboration with artisanal fishers from fishing associations in Cadaqués and Port de la Selva (Figure 1). During the 2018 and 2019 fishing seasons (from March to August), a total of 9 fishers worked in collaboration with scientists to recover the *E. cavolini* colonies entangled in their nets. Collected colonies derived from trammel net fishing targeting lobster at 70–100 m depth. Once disentangled from the net, gorgonians were kept on board in seawater-filled buckets (∼22–25°C) until their transport to land (within 2 hours, at most) where they were held in aquaria installed at both harbours (Cadaqués and Port de la Selva), under environmental conditions similar to those on the continental shelf. Aquaria were composed of 100-L tanks (4 in Port de la Selva and 2 in Cadaqués) filled with seawater filtered using a biological filter (EHEIM 1500XL) and maintained at 13 ± 1.0°C by chillers (Teco TK 2000). A submersible pump (Sicce Nano 2000) provided continuous water movement in each tank. Seawater was partially changed and renewed at least twice a week (approximately 1/3 of the water at each water change). Gorgonians were held under these conditions for a minimum of a few weeks to a maximum of three months and then were prepared for their reintroduction to the continental shelf. During this time, no additional food was added to the tanks to prevent nutrient increase, and gorgonians fed on the particulate organic matter incoming with the regular water changes. Colonies were fragmented into medium size nubbins (16.6 ± 0.6 cm height, mean ± SD), according to the size that showed the highest probability of success by the restoration method used (see details in Montseny et al., 2020). Additionally, necrotic portions were discarded. Natural cobbles and artificial concrete ones were used as supports for gorgonian fragments in the restoration. Natural cobbles (approximately 9–10 cm width, 12–13 cm length, 3–5 cm height, and 400–500 g weight) were collected from the coastal area of Cap de Creus, whereas small artificial cobbles were produced in concrete using a square mould (width: 8.0 cm, length: 8.0 cm, height: 2.5 cm, weight: 175 g) (see details in Montseny et al., 2020). Cobbles were painted with white water-resistant and non-toxic paint to enhance visibility once returned to the continental shelf (Figure 2A). A hole (1 cm diameter, 2 cm depth) was drilled in each cobble in order to allow attachment of gorgonian fragments using an epoxy putty (Corafix SuperFast, GROTECH®) (Figure 2B). All the obtained transplants were maintained in the aquaria facilities installed at both harbours and under the same condition as described above. Once approximately 50 transplants were ready in the tanks, they were reintroduced to the continental shelf. Before their return, transplants were individually photographed on a ruled table in order to record gorgonian size and to allow for future growth monitoring after their reintroduction on the continental shelf. Three locations on the continental shelf within the Cap de Creus Natural Park area were selected as restoration sites: "Golfet" (42° 20′ 42′′ N - 03° 15′ 02′′ E; 64–68 m depth), "Cala Sardina" (42° 20′ 54′′ N - 03° 16′ 12′′ E; 82–86 m depth), and "Portaló" (42° 20' 23′′ N - 03° 17' 35′′ E; 82–90 m depth) (Figure 1). These locations were selected based on the presence of horizontal bottoms in the natural bathymetric range of the species, and because natural populations of *E. cavolini* were known to be located nearby (Dominguez-Carrió, 2018). Even if artisanal trammel net fishery is allowed inside the natural park area, regulation strictly forbids bottom trawling fishing, providing at least a partial protection of the restored sites. A total of 9 return events were performed from June to August 2018, and 8 return events from June to August 2019. During each event, transplants were kept in portable plastic fridges (75 x 40 x 30 cm) filled with seawater (∼13°C) and transported by boat to the restoration sites where they were gently thrown from the sea surface (Figure 2C and D).

Transplants on the continental shelf were monitored in order to assess the success of the restoration action through two consecutive surveys (November 2018 and September 2019) by means of the Girona 500 Autonomous Underwater Vehicle (AUV). The AUV records videos and acquires geo-referenced photo-mosaics of the three restored sites, and of an adjacent natural gorgonian population to be used as control site. The vehicle was equipped with two high definition cameras: one pointing down to acquire a geo-referenced photo-mosaic of the area and the other pointing forward to identify the gorgonians. Two parallel lasers were also included to provide accurate measurements of the forward-looking camera, as well as a set of underwater lights to illuminate the area. The Girona 500 AUV is equipped with a complete navigation suite that includes a MEMS-based attitude sensor, a Doppler velocity logger, a pressure sensor and an ultrashort baseline system that allows tracking and correcting the AUV position with respect to a surface vessel. The photo-mosaics were generated using image registration (Elibol et al., 2016) combined with a pose-graph optimization step which takes into account the navigation information of the AUV (Campos et al., 2016). Given that the seafloor was essentially flat, a 2D image registration approach was chosen, instead of a full 3D reconstruction, as it allowed better handling of cases of low overlap between images (Gracias et al., 2017).

2.3 Ecological evaluation

During each year, the total number of gorgonians recovered from artisanal fishers and their survival in the aquaria were quantified, as well as the total number of transplants obtained from the surviving gorgonians and returned to the continental shelf in each restoration site. By analysing the pictures of the transplants prior their reintroduction, the maximum height of each gorgonian fragment was measured using the Macnification 2.0.1 software (Schols and Lorson, 2008). Subsequently, the size structure of the reintroduced gorgonians was determined for each site and analysed in terms of descriptive statistics using distribution parameters such as skewness and kurtosis. Statistical analyses and graphics were performed with R (RCore Team, 2018) by means of the R Studio software (RStudio Team, 2016) using the ´Ggplot2´ (Wickham, 2016) and the ´Moments´ packages (Komsta and Novomestky, 2015).

The area covered by transplants (m^2; ha) and the restoration success at each site was determined through the analysis of the videos and photo-mosaics recorded with the AUV. The restored area was quantified from the photo-mosaics, whereas the restoration success was evaluated by quantifying the percentage of upright and overturned transplants. In addition, the spatial structure of the gorgonians was assessed and compared between restored and control sites from the analysis of the geo-referenced photo-mosaics. The spatial distribution of the gorgonians and their corresponding coordinates were obtained by using a geographic information system software (QGIS 3.12.0). From these coordinates the gorgonian spatial structure was analysed by applying spatial statistics with Passage 2.0 software package (Rosenberg 2008). The distances between pairs of gorgonians were quantified and plotted with histograms. The restored and control areas were divided into 2 x 2 m grids and the mean colony density in each square plus the percentage of occupancy (percentage of occupied squares) were calculated. Finally, the gorgonian distribution pattern was evaluated using Ripley’s K-function, a second-order spatial statistic which was plotted as an L-function ($L(t) = t – K(t) / 2$) (Fortin and Dale, 2005). In Ripley’s K-function, the number of neighbouring colonies within a distance (t) of each gorgonian colony is counted, and an edge correction is applied to colonies near the border of the photomosaic (Fortin and Dale, 2005). Following this, the null hypothesis of a complete spatial randomness in the distribution of gorgonian colonies was tested by comparing with distributions generated by randomly repositioning all the observed colonies. For statistical significance a 95% confidence interval was set, and 999 randomizations were used. If the sample statistic was found within the bounds of the confidence interval at any point, then the null hypothesis could not be rejected. A significant positive deviation of the sample statistic indicates overdispersion of the colonies, whereas a significant negative deviation indicates a clumped distribution (Fortin and Dale, 2005).

2.4 Economic evaluation

The economic cost of the restoration action and the local fisher's collaboration was evaluated, including the installation and operational costs (Edwards et al., 2010; Medrano et al., 2020; Pagès-Escolà et al., 2020). The restoration action was divided into 5 different phases (Chamberland et al., 2017; Edwards et al., 2010), and estimated costs were broken down into: (1) collection of the by-catch gorgonians, (2) set-up of aquaria facilities for gorgonian maintenance, (3) transplant preparation, (4) transfer and deployment of transplants to the restoration sites, and (5) monitoring of the restoration sites. Salaries of the scientific staff that supported all the phases of the restoration action were accounted separately and according to the base salary for research technician personnel, established by the Spanish Government (2018). Labour was expressed in terms of person-hours only including the time invested in the restoration action. Additionally, a monetary contribution per year was paid to each artisanal fishers for their commitment to collect all the accidentally fished gorgonians during the entire fishing season (6 months, every year).

3. Results

3.1 Ecological evaluation

A total of 805 colonies of *E.cavolini* were recovered from trammel nets during the two studied fishing seasons (468 colonies in 2018 and 337 colonies in 2019). While being maintained in aquaria installed in both harbors, several gorgonian colonies recovered from partial breakage and tissue abrasion they had initially suffered due to the fishing impact. Even so, those gorgonians presenting severe signs of necrosis (22.6%) were rejected and not used for transplant preparation. As a result of this selection, 625 gorgonians (77.6%) were considered suitable for transplantation and were cut into medium-sized fragments, thus increasing the number of nubbins transplanted on supporting cobbles to 864 (representing a 27.7% increase compared to the initial number of colonies). Of these transplants, 38 were discarded (4.4%) which showed additional necrosis, thus resulting in a total of 826 transplants reintroduced to the continental shelf. In total, 693 transplants were placed on natural cobbles and 133 onto artificial small concrete cobbles (see details in Table 1). Based on the experience from 2018 (see below), only natural cobbles were used in 2019 and all transplants were reintroduced at "Portaló". Analyzing the size structure of the reintroduced gorgonian fragments, a dominance of medium-sized colonies (10–20 cm) was observed at all sites. More specifically, skewness and kurtosis values indicated that reintroduced populations were significantly positively skewed, indicating the prevalence of smaller sizes at "Golfet" and "Portaló", while those at "Cala Sardina" were clearly dominated by 15–20 cm height colonies (Table 1 and Figure 3).

The AUV surveys revealed significant differences in the three locations selected for the restoration action in 2018. The restoration failed at "Golfet" (where an area of 2 339.5 m^2 was inspected) because the bottom was found to be covered by seagrass leaves (*Posidonia oceanica*), completely covering the reintroduced gorgonians (only some branches were visible coming out in-between the leaves). Likewise, at "Cala Sardina" (where 2 937.2 m^2 were prospected) the majority of the detected gorgonian transplants were partially or completely buried in fine sediment, hampering their proper identification. In contrast, "Portaló" (where 596.1 m^2 were inspected) turned out to be the most appropriate location for the reintroduction, since 146 gorgonian transplants (out of 151 reintroduced) were correctly detected in 2018, representing 96.7% of all the reintroduced transplants at that site (97.0% on natural cobbles and 88% on small artificial cobbles). A 88.8% of gorgonians transplanted on natural cobbles were landed in a correct upright position, compared to only 72.7% of transplants on small artificial cobbles. In total, the 83.8% of fragments transplanted were correctly landed (Figure 4). Given the failure in "Golfet" and "Cala Sardina" and the lower success of upright landing shown by small artificial cobbles only natural cobbles were used, and all transplants were devolved to "Portaló" in 2019. The AUV survey in 2019 (area inspected 2 330.30 m^2) detected 460 gorgonian transplants, which represented 87.5% of all the reintroduced transplants during the two consecutive years. The majority of the detected transplants were in upright position (416; 90.4%) covering a restored area of 0.23 ha (Figure 4).

The photo-mosaic acquired at “Portaló” allowed detection of a total of 116 transplants, 16 of them were overturned and 100 maintained a correct upright position (86.2%) (Figure 5). Due to technical difficulties in positioning of the AUV under the strong current conditions encountered on the continental shelf, part of the restored area was left uncovered, preventing the identification of all the transplants. From the 100 upright detected transplants, their spatial structure was analysed and compared to the control site (Figure 6), where 799 natural *E. cavolini* colonies were detected in an area similar to “Portaló” (2,365 m^2). Transplants in “Portaló” were more dispersed than in the control site, where the distances between pairs of colonies were shorter (Figure 6B). The mean colony densities per square (2 x 2 m) were 5.3 ± 5.4 (mean± SD) and 1.2 ± 0.6 (mean± SD) at the control site and “Portaló”, respectively. In accordance, the percentage of occupancy was also higher in the control site (23.7%) than in “Portaló” (13.5%). The distribution pattern displayed a clumped distribution of colonies from a scale of 10 cm distance, at both sites (Figure 6C).

3.2 Economic evaluation

A total cost of approximately 106 783 € was calculated for the whole restoration action of 826 gorgonian transplants reintroduced to the continental shelf of Cap de Creus (Table 2 and Supplementary Material Table A1 and A2). Nevertheless, taking the sum of the three inspected areas as the total restored area, the standardized cost per hectare was of 140 504 € ha^{-1}. The highest costs were related to the collection of by-catch gorgonians, and the monitoring of the restored sites (accounting for >80% of the total cost). Conversely, the setup and maintenance of the aquaria, transplant preparation and reintroduction only accounted for 3.5% of total costs (without including scientists' salaries, which accounted for a considerable 14.2% of total cost) (Table 2A). Focusing only on expenses of the transplant preparation and reintroduction stages, the cost of restoring a single gorgonian colony attached to a natural cobble (1 €) was half of the cost when using transplants with small artificial cobbles (2 €) (Table 2B).

4. Discussion

The present study demonstrated, for the first time, the feasibility of restoring a large number of cold-water gorgonians (about 400 colonies) at 80–90 m depth at a low-cost and working in close cooperation with local artisanal fishers. The results represent a first step to achieving comparable spatial and size structure to natural reference populations of *E. cavolini* in a similar bathymetric range (Bo et al., 2012). In the successfully restored site (“Portaló”) the dominance of medium-sized colonies (10–20 cm height) will drive the faster recovery of the ecosystem functioning, and services that gorgonian populations provide (Horoszowski-Fridman et al. 2015; Geist & Hawkins 2016). The area covered at this site was about 0.23 ha, which exceeds most of the current coral restoration projects, mostly conducted at relatively small spatial scales with a mean restored area of 100 m^2 (Boström-Einarsson et al., 2020) However, these results are still far from matching the scale of anthropogenic degradation of ecosystems (10–1,000,000 ha.) (Bayraktarov et al., 2016).

During the initial phase of the restoration action, recovered gorgonians successfully overcame the mechanical damage and stress suffered after being accidentally fished and transported to aquaria facilities. During transport on fishing boats the gorgonians were exposed to high temperatures, suffering an abrupt thermal change in a short time. However, after their transfer and maintenance in aquaria kept at their normal habitat temperature (~13°C), a large proportion of gorgonians recovered from mild signs of necrosis. This contrasts with the generally recognized complexity of *ex situ* maintenance of CWC species (Orejas, 2019), at least for some species. In our case, with relatively simple, low-cost (2 762€) and easy to maintain aquaria installations, only 23% of the collected gorgonians failed to recover, and thus were discarded for transplant preparation. This latter supports the previously demonstrated high recovery capacity of *E. cavolini* (Fava et al., 2010; Montseny et al., 2020, 2019) and proves the possibility of taking advantage of by-catch colonies that otherwise would be discarded. Moreover, since fishing activity generally covers an extensive area, there would potentially be a high genetic diversity of transplants, increasing the success probability for long-term viability of restored populations (Reynolds et al., 2012).

The selection of restoration sites was determined by suitable local conditions for the development of *E. cavolini*, including depth range, bathymetric profile, proximity of natural gorgonian populations, and degree of protection. The restoration sites were located within the Natural Park area where bottom trawling is restricted. Even so, the first monitoring highlighted that the restoration action failed at two out of the three selected sites, due to the presence of fine sediment and dead seagrass leaves making it impossible to properly detect the reintroduced transplants. Contrarywise, at the “Portaló” site the two-years AUV monitoring allowed us to successfully detect more than 85% of the reintroduced transplants. These results underline the importance of considering the environmental conditions for a proper selection of restoration locations, since environmental conditions display a critical role in shaping the outcomes of restoration projects (Boström-Einarsson et al., 2020; Suggett et al., 2019). Several ecological restoration actions have failed due to the complexity of accounting for all the stressors influencing the system (Bruckner et al., 2008; MBARI annual report, 2016; Zedler and Callaway, 2000). However, most of those failures are often unreported (Precht and Robbart, 2006). Selection of proper sites for the restoration actions is especially challenging for deep-sea locations, where limited knowledge of environmental conditions and spatial and temporal dynamics, together with the difficulties in predicting future scenarios, can contribute to unexpected consequences affecting restoration efforts (Abelson, 2006).

The high percentage of transplants found alive and in upright position is in close accordance with forecasts from the previous evaluation study of the used technique (Montseny et al., 2020). The arborescent morphology of the gorgonian colonies leads to a successful landing in upright position on the continental shelf when attached to a cobble. Once there, transplants are likely to survive in the long-term, as previously suggested by small-scale trials for *E. cavolini* (Montseny et al., 2019) and other Mediterranean shallower gorgonians (Fava et al., 2010; Linares et al., 2008). High survival rates of transplants were also observed in the few other active CWC restoration attempts performed to date, with coral survival ranging from 52% to 87.5% after 1 to 3 years (Boch et al., 2019; Brooke et al., 2006; Dahl, 2013; Jonsson et al., 2015; Strömberg, 2016). Transplants attached to small artificial cobbles in 2018 showed higher probability of landing overturned than transplants on natural cobbles, thus reaffirming the use of local natural cobbles as the best option for this kind of active ecological restoration (Montseny et al., 2020), as well as avoiding the introduction of artificial material (Weinberg, 1979).

To properly assess restoration success over time it is crucial to establish a reference site for comparison (Aronson et al., 2017; Falk et al., 2006; McDonald et al., 2016). This site should ideally be nearby, undamaged, analogous and pristine (or near pristine), serving to evaluate the success of the performed restoration action over time (Falk et al., 2006; McDonald et al., 2016). However, the fact that artisanal fishing traditionally occurs over the entire study area prevented us from identifying a pristine reference site for our study case. This is commonly the case for most deep-sea areas, for which there is still very limited information about ecosystem baseline conditions (Da Ros et al., 2019), and reference ecosystems have to be inferred from the best ecological knowledge available (Gann et al., 2019; Morato et al., 2018). In our study, we selected a nearby control site with a natural *E. cavolini* population to compare with the restored population at the "Portaló" site. From the photo-mosaics comparison we were able to detect a first establishment of a reintroduced gorgonian population that may trend to a natural population in terms of distribution and density patterns, if natural recruitment occurs. Although current values at the "Portaló" site are far from those in natural control sites, the methodology presented here allowed us to set up a conceptual framework for the monitoring of ecological restorations in deep habitats. Consistent with our results, the successful use of photo-mosaics for the evaluation of CWC has also been proven in very recent studies (Boolukos et al., 2019; Prado et al., 2019). Long-term monitoring (15–20 years) has been highlighted as paramount to proper evaluating success of restoration actions in shallow waters (Bayraktarov et al., 2016), and this is even more crucial for CWC species given their slow population dynamics (Bennecke et al., 2016; Orejas and Jiménez, 2019; Roberts and Hirshfield, 2004). Moreover, applying an adaptive management based on proper monitoring leads to the opportunity to improve restoration results by incorporating lessons from failures (Hackney, 2000; Precht and Robbart, 2006), such as the correct selection of the restoration sites in our study case. The short duration of our monitoring period (two years) allowed for a proper assessment of the initial rate of transplant survival, as well as for comparing the restored population with natural ones in terms of population size and spatial structure (establishing a paramount baseline of information for future comparisons). Nonetheless, our monitoring period precluded the detection of any recruitment or growth. Most coastal marine restoration projects, even for shallower environments, are performed during short period times (less than two years). This throws into doubt their adequacy for assessing recovery of ecosystem functioning, since outcomes of restoration are directly related with the monitored time period (Bayraktarov et al., 2016). Therefore, enlarging the time scale of monitoring, especially in the deep-sea, is a necessity for obtaining reliable evaluation of restoration success.

Given the sophisticated technologies and infrastructures (e.g., oceanographic vessels, ROVs (Remotely Operated Vehicles) and AUVs) involved in the whole process of restoring and monitoring deep-water environments, these actions still nowadays are a costly effort. Restoration costs usually exceed millions of dollars, ranging from US$ 1.2 to 4.4 M ha^{-1} during the first year (Da Ros et al., 2019; Van Dover et al., 2014). For the present restoration action, the fisher's monetary contribution, the monitoring of restoration sites, and scientists' wages, required more than 80% of the project budget (Table 2; and Supplementary Material Table A1 and A2). Although these latter costs are highly dependent on local conditions such as fuel prices, distance to the restoration sites and country salaries, they could be significantly reduced by applying several improvements towards a more routine application, reducing the involvement of scientists and increasing local participation of fishers and stakeholders. Furthermore, improving technological development to obtain specialized, cheaper and easier-to-use underwater tools would also reduce restoration costs (Van Dover et al., 2014). Indeed, once by-catch colonies have been collected, maintenance in aquaria, preparation of the transplants, and reintroduction to the continental shelf only amounted to 3.5% of the total expenses (3 737 € in total; 4.5 € transplant^{-1}; Table 2). Keeping aside costs related with setting-up aquarium facilities, the cost of restoring a single gorgonian colony attached to a natural cobble is about 1 € (Table 2B). Setting-up aquarium facilities requires an initial investment but has a low annual maintenance cost which reduces overall costs for years to come. Overall, the total costs for the 2-yr restoration action reported here accounted for about 140 000 € ha^{-1}, which is surprisingly more in accordance with the cost of restoring one hectare of marine coastal habitats (from US$ 13 000 to US$ > 1 M ha^{-1}, with a median cost of ~US$ 500 000 ha^{-1}; Spurgeon and Lindahl, 2000; Edwards and Wells, 2010), than the cost estimated for deeper habitats (Van Dover et al., 2014, Da Ros et al., 2019). After one or two years of adaptation, the used method (Montseny et al., 2020) could be a promising cost-effective technique that in itself would not cost more than few euros for each transplant restored. In this sense, the involvement of local communities in the restoration action is key for the success of long-term application. As in the present example, through their local knowledge and meaningful sensitivity to existing conditions, cooperation of local fishers is a great opportunity to enhance the effectiveness of restoration actions (Hull and Gobster, 2000; Yap, 2000). From the experience of these two years of project implementation, we perceived a growing interest of fishers in CWC gardens and a greater willingness to protect them and reduce the fishing impact. Restoration actions, involving local actors (fishers, managers and stakeholders) could also be an advantage for connecting civil society with the natural environment. From the local actors' point of view, being part of restoration activities can offer an opportunity to participate in the sustainable management of the habitats that guarantees their current and future source of income and resources, while prompting personal growth by achieving the satisfaction of making a difference (Miles et al., 1998).

5. Conclusions

In conclusion, the low-cost, low-tech and wide-scale applicable methodology presented here could be potentially extended to other CWC gardens, fostering a society-based implementation by involving local actors and using by-catch gorgonians. However, the importance of combining this active restoration with passive restoration measures such as marine protected and managed areas (Davies et al., 2007; Gubbay et al., 2003) to prevent or reduce impacts from anthropogenic disturbances and to ensure habitat recovery should also be noted. A total protection of restored areas would be ideal (Bennecke and Metaxas, 2017; Huvenne et al., 2016), but in turn challenging to apply in every situation. In fact, artisanal fishing practices impacting gorgonians populations will continue in the Cap de Creus Natural Park. Therefore, a complementary measure would be to search for alternative fishing gears that ensure a commercial catch while reducing the by-catch.

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TABLES AND FIGURES

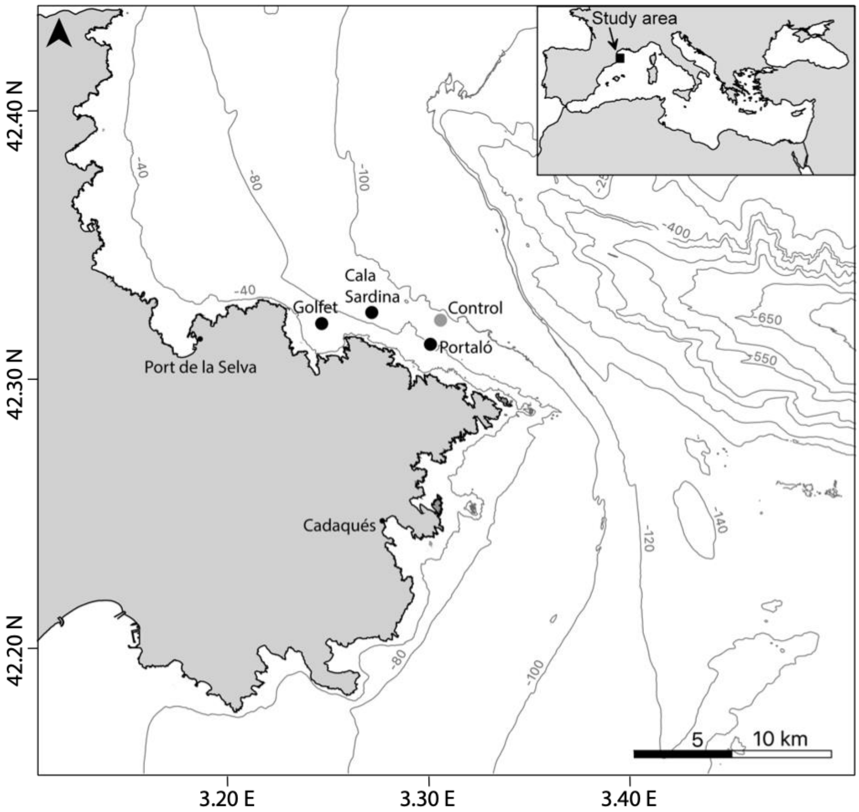


Figure 1. Study area with the three restoration locations in black (Golfet - Cala Sardina - Portaló) and the control site in grey (close to Portaló) (UTM31 WSG84).

Figure 2. Restoration action images. (A) Drilled and painted natural cobbles (photo credit ICM-CSIC); (B) Gorgonian fragment attached to a natural cobble using epoxy potty (photo credit L.

Sabaté); (C and D) Gorgonian transplant gently thrown from a boat (photo credit ICM-CSIC and N. Viladrich).

Site	**Year**	**Nº colonies**		**Height (cm)**			**Skewness**			**Kurtosis**		
		NC	SAC	Mean± SD	Max	Min	Skew	*p-value*	Sig.	Kurt	*p-value*	Sig.
Golfet	2018	100	50	15.48±3.63	26.77	7.12	0.809	<0.001	***	3.687	0.092	
Cala Sardina	2018	117	33	16.26±4.06	28.64	8.48	0.373	0.056		2.885	0.960	
Portaló	2018 and 2019	476	50	17.23±4.61	34.95	6.2	0.246	0.021	*	2.924	0.827	

Table 1. Number of reintroduced transplants and size structure (height, skewness and kurtosis) for each restoration site and year. Significant skewness or kurtosis are indicated with asterisks. NC = natural cobbles, SAC = small artificial cobbles.

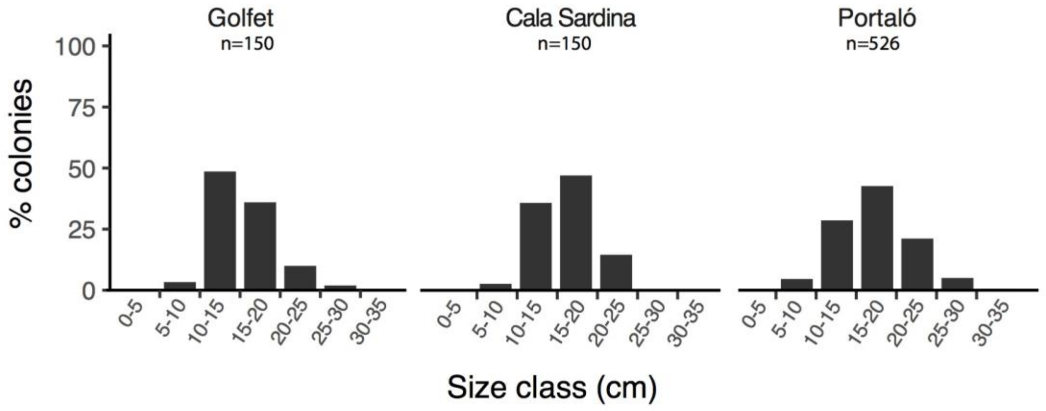


Figure 3. Size frequency distribution of *E.cavolini* transplants reintroduced at each restoration site (n = number of transplants). Note that Portaló includes all the cumulative transplants reintroduced in 2018 and 2019.

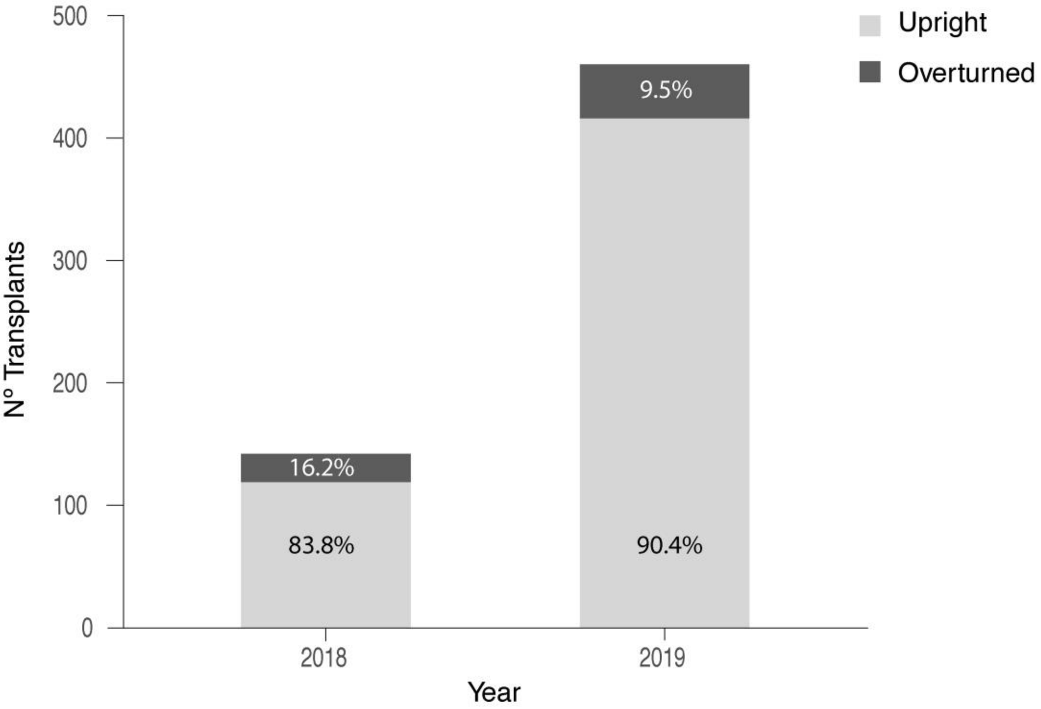


Figure 4: Number of upright (grey) or overturned (black) transplants detected at Portaló (82–90 m depth) during the AUV monitoring surveys in 2018 and 2019. Note that 2019 includes all the cumulative transplants reintroduced in 2018 and 2019.

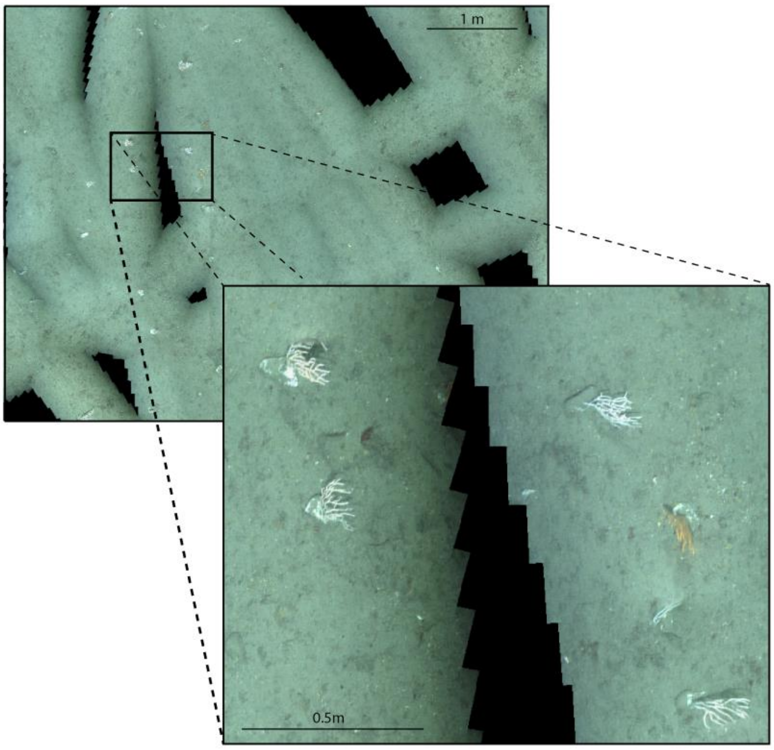


Figure 5: Photo-mosaic section obtained during the AUV monitoring at Portaló in 2019.

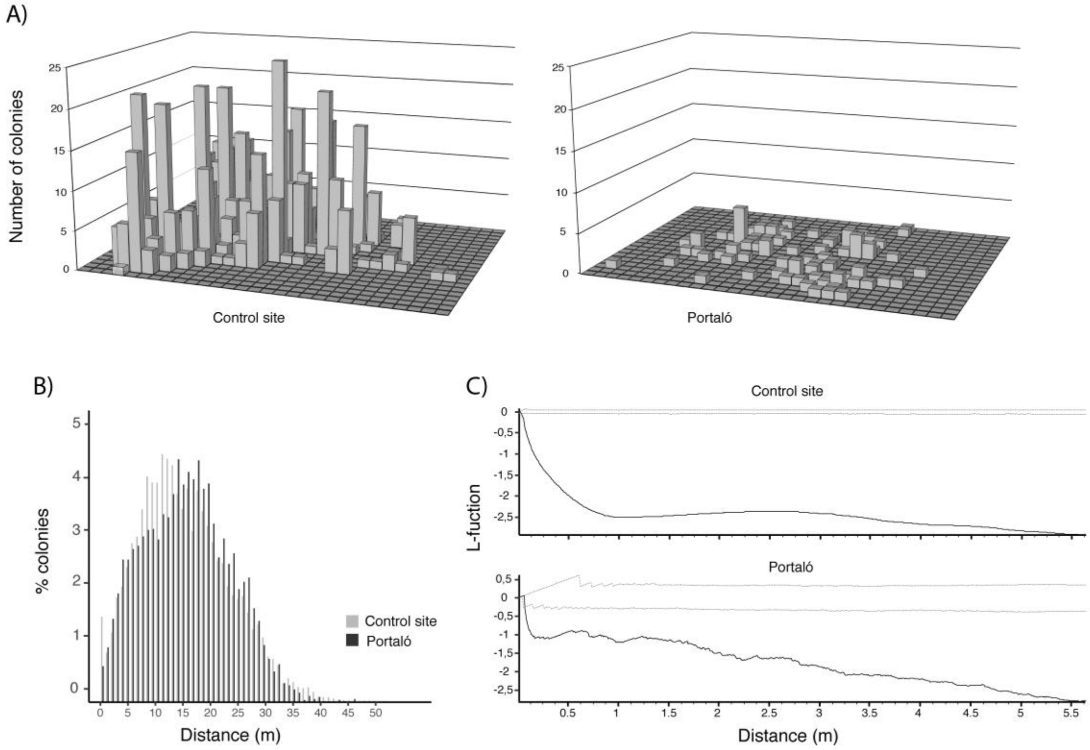


Figure 6. Comparison of colonies' spatial structure between the control site and the restored Portaló site in 2019. A) Colonies density pattern in control site (2 365 m^2) and Portaló (2 330 m^2); B) Distribution of distances between pairs of colonies; C) Colonies distribution pattern by the L-function (derived from Ripley's K-function).

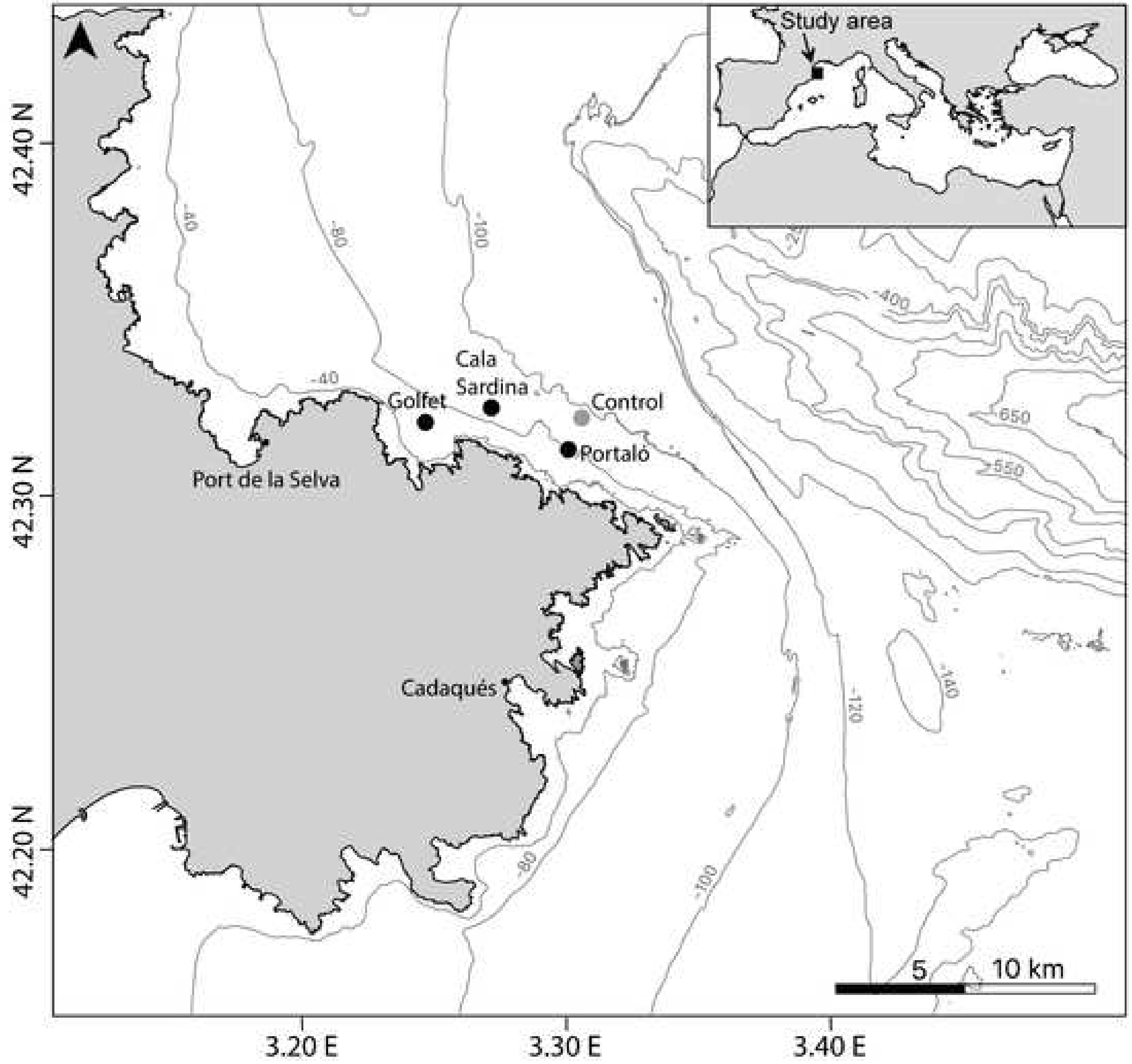
Table 2: (A) Summary table of the estimated costs for the restoration action resulting in 826 restored transplants. (B) Calculated costs for preparation and reintroduction of a single gorgonian transplant, according to the cobble type.

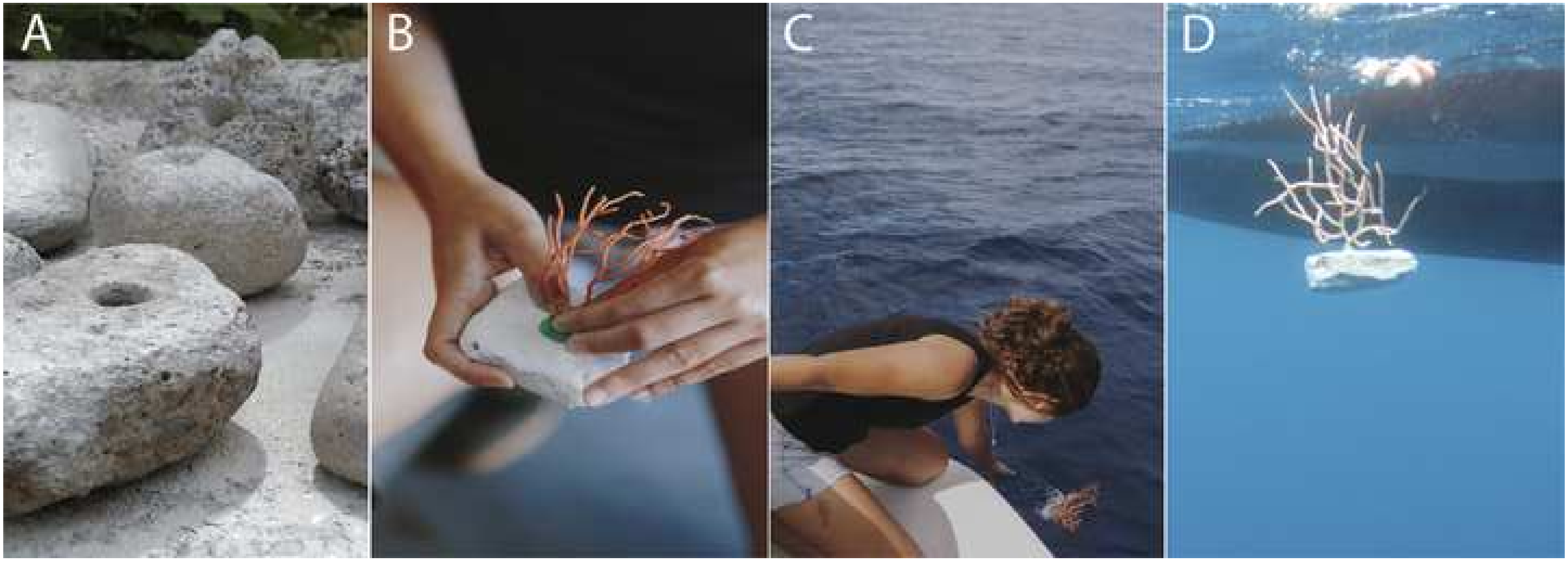
A)

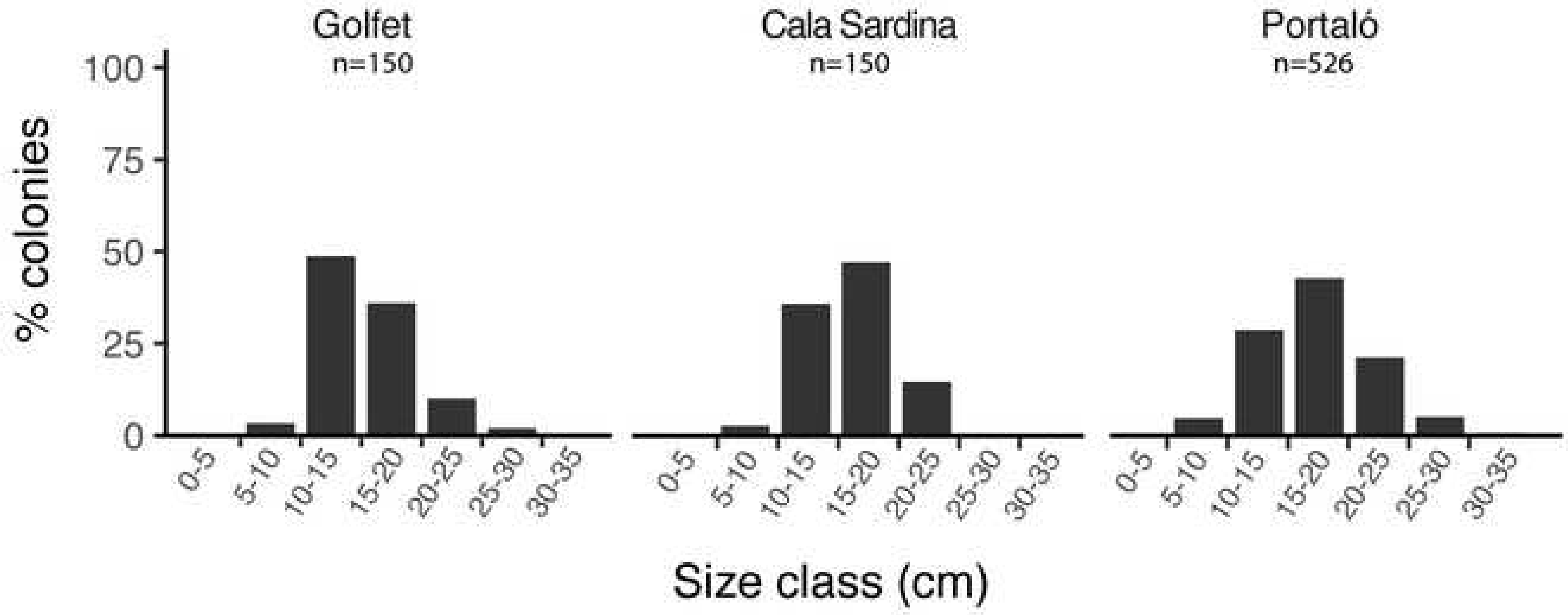
Concept	*Total (€)*	*% of the total costs*
Collection of by-catch gorgonians	54 000	50.57
Setup of aquarium facilities	2 762.58	2.59
Transplants preparation	460.27	0.43
Transfer and deployment of transplants to restoration sites	514.5	0.48
Monitoring of the restoration sites	33 880	31.37
Scientists' salaries	15 165.36	14.20
TOTAL RESTORATION COST	106 782.71	100

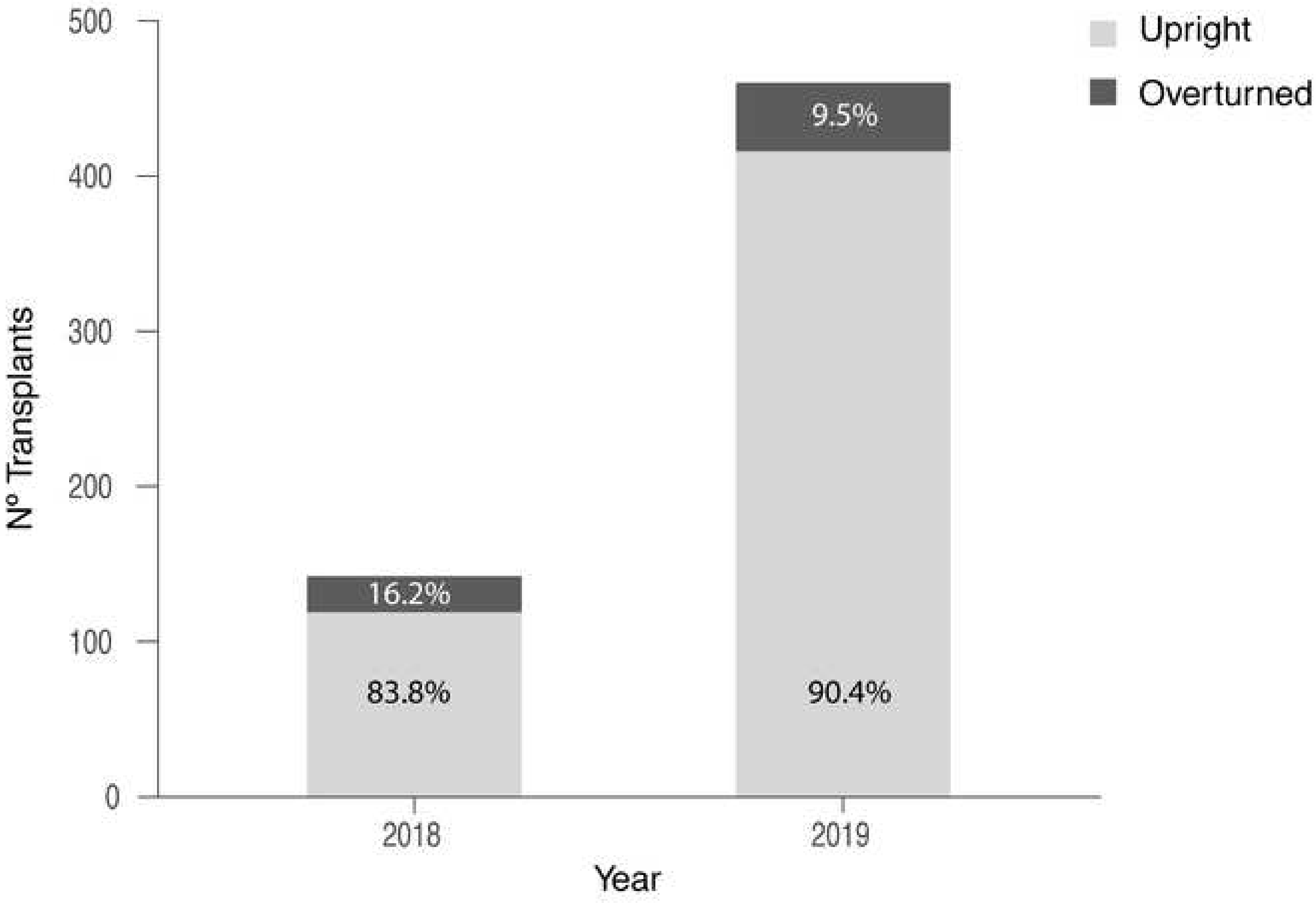
B)

Concept	*Cost (€) / NC transplant*	*Cost (€) / SAC transplant*
Transplants preparation	0.54	0.94
Transfer and deployment of transplants to restoration sites	0.53	1.07
TOTAL	1.07	2.01

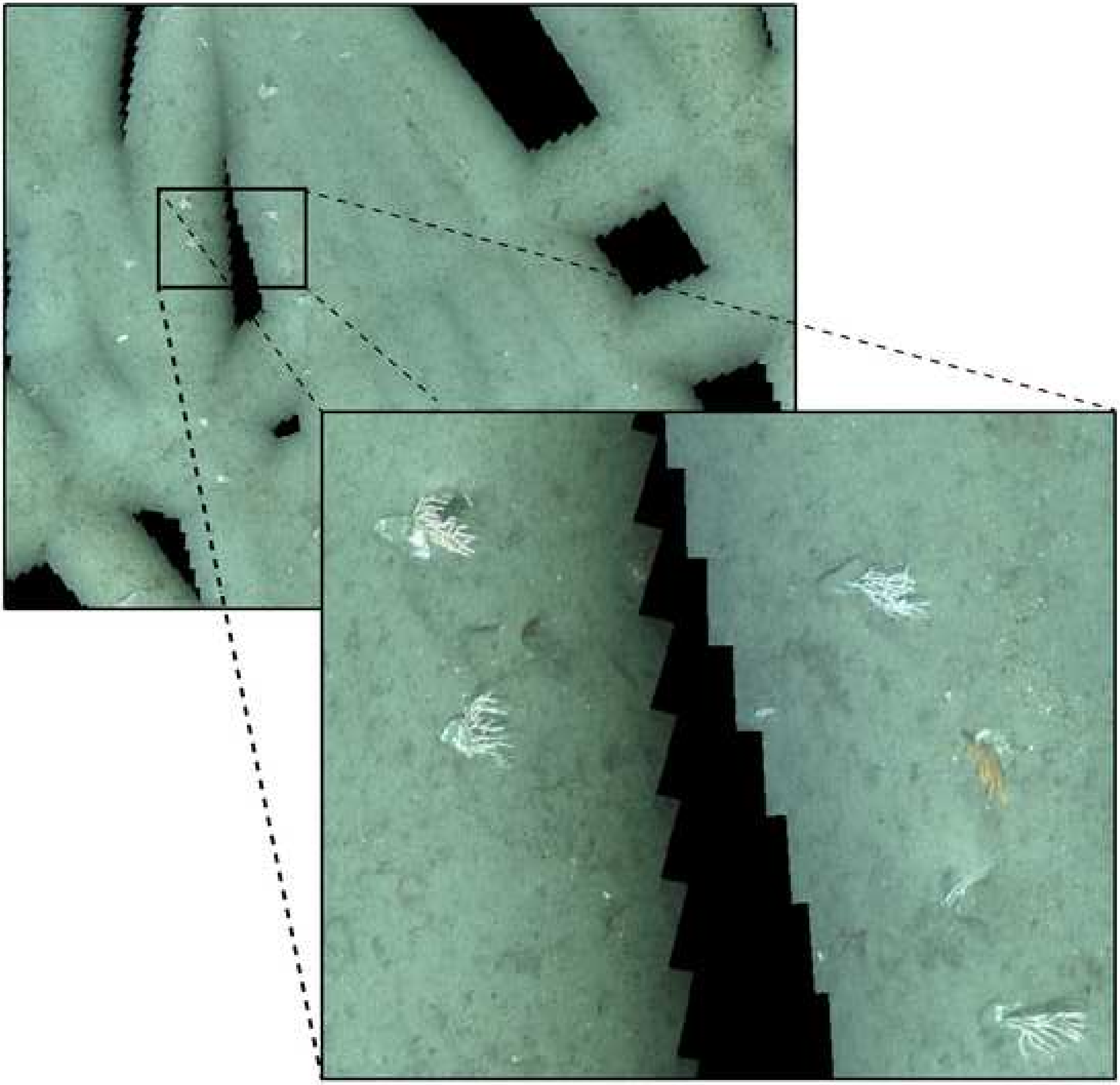

Study area
Cala Sardina
Golfet
Control
Portaló
Port de la Selva
Cadaqués
-40
-80
-100
-120
-140
-400
-650
-550
5
10 km
42.40 N
42.30 N
42.20 N
3.20 E
3.30 E
3.40 E

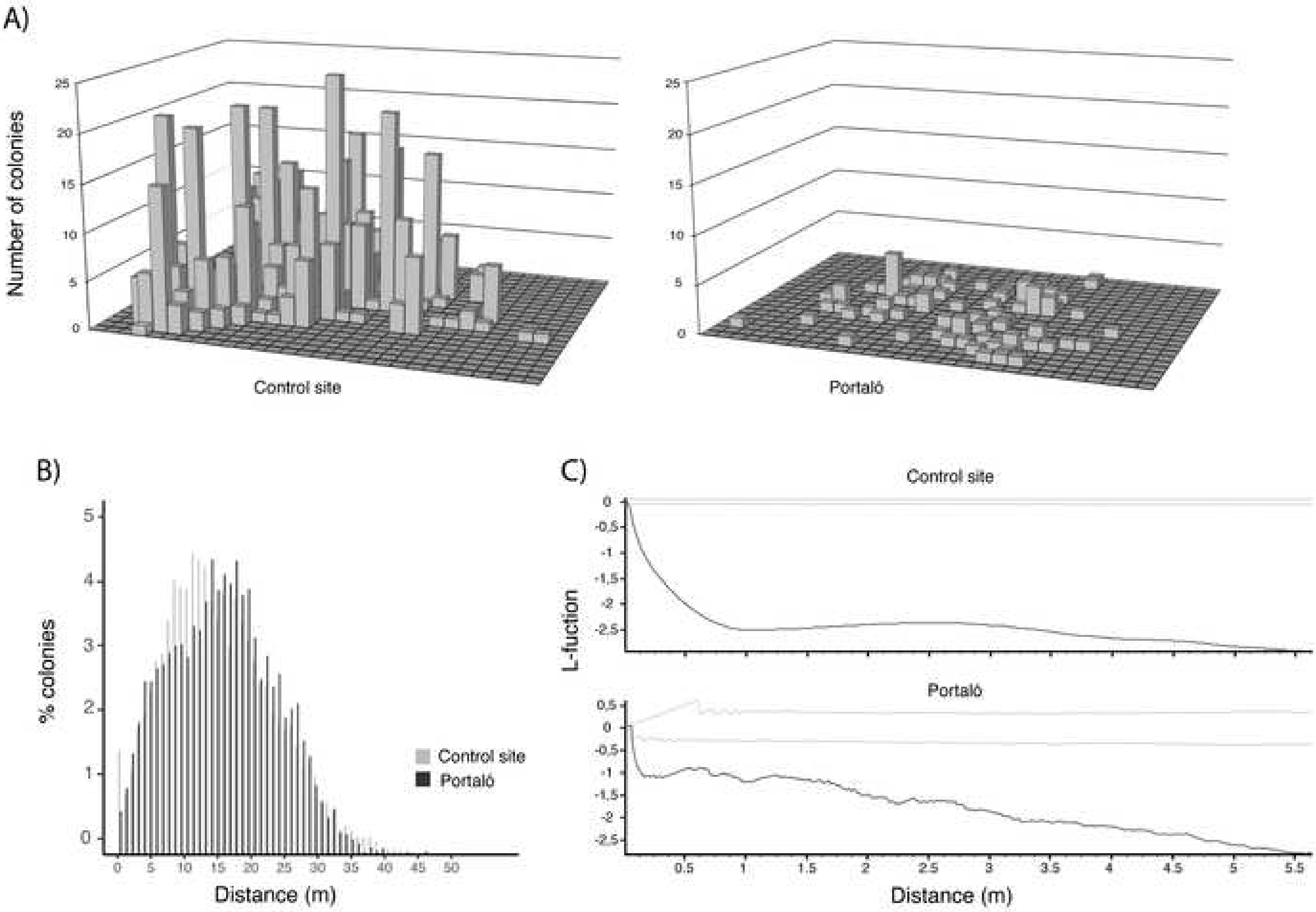

A
B
C
D


Golfet
n=150
Cala Sardina
n=150
Portaló
n=526
% colonies
100
75
50
25
0
0-5
5-10
10-15
15-20
20-25
25-30
30-35
Size class (cm)



500
400
300
200
100
0
Nº Transplants
Upright
Overturned
16.2%
83.8%
9.5%
90.4%
2018
2019
Year




A)
Number of colonies
25
20
15
10
5
0
Control site
Portaló
B)
% colonies
5
4
3
2
1
0
0 5 10 15 20 25 30 35 40 45 50
Distance (m)
Control site
Portaló
C)
Control site
L-fuction
0
-0,5
-1
-1,5
-2
-2,5
Portaló
0,5
0
-0,5
-1
-1,5
-2
-2,5
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5
Distance (m)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Supplementary Material

Table A2_supplementary material.xlsx