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A new large-scale and cost-effective restoration method for cold-water coral gardens

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Abstract

1. Gorgonians dwelling on the Mediterranean continental shelf are among the most frequent fishing bycatch taxa. These species display several traits, such as long lifespans and slow growth, which make them very vulnerable to the impacts caused by fishing activities with far-reaching and long-lasting effects.
2. Hence, restoration and mitigation actions are crucial to enhance and speed up the natural recovery of damaged cold-water coral gardens. Given the growing concern to develop effective and affordable restoration actions, the present study aims to propose and technically validate a new large-scale and cost-effective restoration method.
3. This technique, named 'badminton method', consists of attaching bycatch *Eunicella cavolini* colonies to cobble supports and returning them to the continental shelf by gently throwing the gorgonian transplants directly from a boat.
4. Two consecutive field experiments were conducted in order to find the best cobble type support and gorgonian size to be used: first, to evaluate the landing efficiency of gorgonian transplants at different depths (from 5 to 30 m) and second, to evaluate their capability to maintain a correct position over time.
5. Natural cobbles with large gorgonians attached were the best option. Field results and modelling approaches suggest that the transplants would correctly land on the continental shelf seabed in a predicted area of around 60 m². Moreover, they would successfully maintain an upright position ensuring gorgonian survival over time.
6. The success of this method highlights the feasibility of large-scale and low-cost restoration actions with promising results for the conservation and recovery of cold-water coral gardens.

KEYWORDS

benthos, conservation evaluation, coral, fishing, new techniques, recovery

1 | INTRODUCTION

Over recent decades, the increasing attention towards deep water ecosystems and the continued advancements in deep sea exploration technology have contributed to expand knowledge about benthic

communities dwelling on continental shelves (~60–200 m depth) and deep sea bottoms (>200 m depth) (Althaus et al., 2009; Freiwald, Fossa, Grehan, Koslow, & Roberts, 2004). At depths of 60–1000 m, cold-water corals and sponges are among the main habitat-forming species, generating complex three-dimensional ecosystems that

create hotspots of biodiversity over large areas (Hovland, 2008; Roberts, Wheeler, Freiwald, & Cairns, 2009). They provide suitable habitat, acting as feeding, reproductive, nursery, and refuge areas for a wide variety of associated species, many of which are of commercial interest (Cartes, Lolocono, Mamouridis, López-Pérez, & Rodríguez, 2013; Henry & Roberts, 2007; Krieger & Wing, 2002). At the same time, cold-water coral reefs, coral gardens, and sponge grounds also play an important role in the benthic–pelagic transfer of energy and matter (Gili & Coma, 1998; Graf, 1989) as well as in most of the biogeochemical cycles of the deep sea (Cathalot et al., 2015; Coppari et al., 2016; Van Oevelen et al., 2009).

The continuously increasing exploitation of deep sea resources is currently recognized as a major threat (Jackson et al., 2001; Morato, Watson, Pitcher, & Pauly, 2006). Since the last century, continental shelves and upper slopes have been heavily impacted by fishing activities (Jones, 1992; Koslow et al., 2000; Oberle, Puig, & Martín, 2017). Bottom trawling represents one of the main threats to benthic ecosystems (Clark et al., 2016; Hall-Spencer, Allain, & Fossa, 2002), resulting in a severe oversimplification of benthic communities (Reed, Koenig, Shepard, & Gilmore, 2007; Thrush & Dayton, 2002; Watling & Norse, 1998). However, in rocky areas with complex topography inaccessible to trawling, artisanal fishing can also jeopardise the integrity of benthic ecosystems (Angiolillo & Canese, 2018; Sampaio et al., 2012).

In the Mediterranean Sea, gorgonians are among the most frequent species of bycatch of artisanal trammel net and longline fishing in coastal areas and on the continental shelf. Due to their arborescent morphology and erect position, gorgonians are easily entangled in bottom-contact fishing gears (Deidun et al., 2015; Mytilineou et al., 2014). These fishing gears can remove entire gorgonian colonies, or partially damage their tissue, making them more vulnerable to diseases and/or epibiont overgrowth (Angiolillo et al., 2015; Bo, Bava et al., 2014; Bo, Cerrano et al., 2014). Since most Mediterranean gorgonians are long-lived, slow-growing species, with delayed sexual maturity and limited recruitment (Coma, Ribes, Zabala, & Gili, 1998; Linares, Doak, Coma, Díaz, & Zabala, 2007), fishing activities impacting their populations can have far-reaching and long-lasting negative effects in their long-term viability (Bo et al., 2015; Bo, Cerrano, et al., 2014). As a consequence, Mediterranean cold-water coral gardens located on the continental shelf and slope have recently been internationally recognized as Vulnerable Marine Ecosystems (Fabri et al., 2014; OSPAR Commission, 2010), stressing the urgent need for their sustainable management and conservation (Aguilar & Marín, 2013; Davies, Roberts, & Hall-Spencer, 2007; FAO, 2009). The conservation and recovery of benthic engineering species such as gorgonians will also help to preserve all their associated fauna, maintaining the ecosystem functioning and the ecosystem services provided (Byers et al., 2006; Geist & Hawkins, 2016). It is, thus, highly desirable to actively initiate or improve the slow natural recovery of impacted cold-water coral assemblages, by means of reducing impacts and assisted regeneration with biotic intervention (i.e. active restoration) (Possingham, Bode, & Klein, 2015; Van Dover et al., 2014).

Ecological restoration offers the opportunity to redirect the environmental damage caused by anthropogenic impacts and assist the

recovery of a natural range of ecosystem composition, structure, and dynamics (Falk, Palmer, & Zedler, 2006; Society for Ecological Restoration International Science & Policy Working Group, 2004). However, until now, most of the actions and initiatives carried out in marine ecosystems have been concentrated on the restoration of shallow habitats, particularly in tropical ecosystems (i.e. Guzman, 1991; Rinkevich, 2005; Young, Schopmeyer, & Lirman, 2012). Only a few restoration attempts have been carried out in the deep sea, specifically targeting cold-water coral species (70–1300 m depth, Boch et al., 2019; Brooke, Koenig, & Shepard, 2006; Dahl, 2013) and coral gardens on the Mediterranean continental shelf (60–120 m depth, Montseny et al., 2019). High survival values of coral and gorgonian transplants were found in these studies, highlighting the feasibility of active restoration of cold-water coral reefs and coral gardens, despite the considerable limitations associated with the difficulties of working at intermediate and deep depths (Clauss & Hoog, 2002).

Among these constraints, the need for advanced underwater technologies is considered to increase the economic cost of any deep sea restoration action compared to shallow areas (Van Dover et al., 2014). Likewise, the difficult and extremely limited access to these habitats also restricts restoration actions and their monitoring to small spatial extents (Brooke et al., 2006; Dahl, 2013). However, since the main stressors impacting most continental shelf and deep sea ecosystems are largely widespread (Halpern et al., 2008), scaling up and reducing economic costs are necessary steps to ensure a long-term viability of deep sea ecological restoration actions.

Based on the demonstrated capability of bycatch gorgonians to survive after their transplantation back into their natural environment (Montseny et al., 2019), the main goal of the present study was to explore the technical viability of a new large-scale and cost-effective restoration method. Gorgonian colonies recovered from artisanal fishery bycatch (trammel nets) were attached to cobble supports, and transplanted to the continental shelf by gently throwing them from the sea surface. The landing efficiency (i.e. successful landing in upright position and dispersion area of transplants) and the capability to maintain the upright position over time were estimated according to depth, the characteristics of the cobbles used, and the size of the transplanted gorgonians. The method has been named 'badminton method' because the fan-shaped morphology of the colonies attached to the cobbles makes them act as a badminton shuttlecock, slowing down the fall and facilitating an upright landing. It was inspired by the common practice of artisanal fishermen from Menorca (Balearic Islands, Spain) to return to the sea gorgonians that they accidentally catch attached to maërl cobbles, by throwing them from the sea surface.

2 | METHODS

2.1 | Studied species

Eunicella cavolini (Koch, 1887) is one of the most common Mediterranean gorgonian species (Carpine & Grasshoff, 1975; Weinberg, 1976),

showing a wide bathymetric distribution (<10–220 m depth) (Bo et al., 2012; Russo, 1985). In general, this non-symbiotic gorgonian presents fan-shaped colonies with a variable ramification pattern and growth rate, depending on environmental conditions. Commonly, the ramifications are numerous and tend to be curved, pointing in many directions although lying in one plane, fully exposed to the main current flux (Velimirov, 1973; Weinbauer & Velimirov, 1995). In the Mediterranean Sea, the mean height of the entire colony is around 15 cm (Sini, Kipson, Linares, Koutsoubas, & Garrabou, 2015) with largest colonies reaching 50 cm height (Bo et al., 2012). In the Cap de Creus area (north-western Mediterranean Sea, 42° 19' 12" N – 003° 19' 34" E), this species is abundant on the outcropping rocks at 80–120 m depth on the continental shelf, forming high density patches reaching densities of 25 colonies m⁻² (Dominguez-Carrió, 2018; Gili et al., 2011).

2.2 | Gorgonian collection and maintenance

Bycatch colonies of *E. cavolini* (5–17 cm height) were collected from trammel nets fishing during summer 2016 with the collaboration of artisanal fishers. The collected gorgonians were kept on board in a bucket filled with surface sea water (~22–25°C). Once on land, colonies were kept in a 100-L tank filled with sea water maintained at 14 ± 1.0°C and with a submersible pump providing continuous water movement. A chiller (Tank chiller line TK 2000) was used to maintain a constant seawater temperature, and the water was filtered using a biological filter (SERA fil bioactive 250+UV). As soon as it was possible (after 1 or 2 days), gorgonians were moved to the Institute of Marine Sciences in Barcelona (Spain) without being adversely affected during the transport. There, gorgonians were held in a 100-L tank with a continuous flow of Mediterranean sea water pumped from a depth of 15 m at a rate of 50 L h⁻¹ and filtered with a 100-µm pore size (Olariaga, Gori, Orejas, & Gili, 2009). A submersible pump provided continuous water movement in the tank with a flow rate of 320 L h⁻¹, seawater temperature was constantly maintained at 14 ± 1.0 °C and gorgonians kept in dark conditions, corresponding to the natural conditions of the Cap de Creus continental shelf (Dominguez-Carrió, 2018). Gorgonians were held under these conditions during a few weeks up to 5 months, being fed three times a week with frozen *Cyclops* (Crustacea, Copepoda).

2.3 | Gorgonian transplants preparation

To identify the best support to be used in this gorgonian restoration method, three different types of cobbles were tested: (A) natural cobbles, (B) small artificial cobbles, and (C) large artificial cobbles (Figure 1). Natural cobbles were collected from the coastal area of Cap de Creus (mean width: 9.7 ± 1.6 cm, mean length: 12.4 ± 1.6 cm, mean height: 3.1 ± 1.0 cm, mean weight: 455 ± 139 g). Artificial cobbles with established measurements were built with concrete: small artificial cobbles had a square shape (width: 8.0 cm, length: 8.0 cm, height: 2.5 cm, weight: 175 g); and large artificial cobbles had a semi-spherical shape (diameter: 13.3 cm, height: 4.5 cm, weight: 450 g). Thirty cobbles in total were used (10 per cobble type). To identify the most effective gorgonian size to be transplanted, large gorgonians (10–17 cm height, 80–300 cm total ramification length) were transplanted on five cobbles per type, and small gorgonians (5–10 cm height, 20–80 cm total ramification length) were transplanted on the other five cobbles per type. Gorgonians were attached to supporting cobbles using epoxy putty (Corafix SuperFast, GROTECH®). All colonies used as transplants did not show any signal of necrotic tissue before being returned to the sea.

2.4 | Landing efficiency

The first part of the field study consisted of assessing the landing efficiency of the gorgonian transplants gently thrown from the sea surface. The dispersion area on the sea floor and success of upright landing were quantified at 5, 10, 20, and 30 m depths (Cap de Creus, 42° 28' 39" N – 003° 28' 31" E). At each depth, the 10 cobbles with five large and five small gorgonians transplanted were gently thrown from a boat. Once at the sea floor, and by means of scuba diving, a hand-drawn map of the 10 transplants was produced by measuring *in situ* the perpendicular distance (cm) between the position of each transplant from a central transect established in the area where the transplants had landed. Finally, the landing success of each gorgonian was estimated by recording *in situ* whether the colonies had landed in an upright or overturned position. This procedure was repeated five times for each cobble type and depth.

FIGURE 1 Gorgonian transplants with different types of cobbles tested in the study. (a) Natural cobbles; (b) small artificial cobbles; and (c) large artificial cobbles

2.5 | Monitoring of transplants

The second part of the field study consisted of assessing whether the transplants, once on the sea floor, maintained the correct upright position over time. To this aim, new gorgonians with no signs of necrosis, were attached to the same three types of cobbles, as previously described. Again, large gorgonians were transplanted on five cobbles per type, and small gorgonians were transplanted on the other five cobbles per type. The resulting 30 cobbles (10 cobbles per type) were placed by hand in an upright position on a horizontal bottom composed of small cobbles and sand at 30 m depth (Cap de Creus, 42° 17' 03" N – 003° 17' 55" E), and monitored by scuba divers in 3 consecutive months. Colonies were individually photographed on a ruled tablet in order to acquire pictures of the transplants with a size reference. From these pictures, the position of the transplants (upright or overturned) was established, and for each gorgonian the amount of necrotic tissue along the total ramification length was quantified to estimate their survival and health status.

2.6 | Data analysis

To analyse the cobbles probability of landing success (response variable) according to depth (explanatory continuous variable), cobble type and gorgonian size (explanatory discrete variables), two model types were fitted: (1) a general linear model (GLM) with a binomial error distribution and a logit link function, (2) a general linear mixed model with a binomial family, identifying individual cobbles as random effect. Finally, only the simplest binomial GLM was plotted, which presented the lowest Akaike information criterion with small-sample correction value (AICc; see Supplementary Material 1). To test the significance effects of depth, cobble type, and gorgonian size, an ANOVA Type II test for non-sequential factors, was applied over the fitted model (GLM). A GLM with a binomial error distribution and a logit link function was also used to predict the probability of successful landing in a hypothetical situation of throwing the transplants up to 80 m depth according to cobble type. Additionally, given the great variability in shape and weight among the natural cobbles used in the experiment, we explored the relationship between the sphericity index (SI) and the weight of cobbles, and their probability of landing upward, using a Spearman rank order correlation (Spearman, 1904). The SI of cobbles (Ψ_p) was calculated from their maximum length, width and thickness measures (Sneed & Folk, 1958).

The total dispersion area (m^2) of the transplants on the sea floor was measured from the maps obtained *in situ* by scuba diving. For each cobble type and depth, the area corresponding to the smallest ellipse that included all the transplants was quantified using the Macnification 2.05 software (Orbicule, Leuven, Belgium). To estimate the area of dispersion in which transplants would extend on the continental shelf (80 m) according to cobble type, different statistical models were built. Depth (continuous variable) and cobble type (discrete variable) were the explanatory variables, while the dispersion area was the continuous response variables. Several GLM models,

non-linear regression model, mixed linear model and GAM model were adjusted to detect which of them showed the lowest AICc value and therefore better fit the data.

Regarding the monitoring transplant study, the evolution of their position (upright or overturned) according to the cobble type was plotted during the 3-month period. Additionally, a Wilcoxon signed-rank statistical test (Wilcoxon, 1945) was performed at the end of the monitoring to detect the influence of gorgonian size in overturning the transplants. To evaluate the status of transplanted colonies and compare them to natural values (Coma, Pola, Ribes, & Zabala, 2004; Linares, Coma, Garrabou, Díaz, & Zabala, 2008), all colonies were photographed during the monthly monitoring at 30 m depth and they were analysed with Macnification 2.05 software. At the end of the 3-month experiment, the percentage of necrosis on the total ramification length ($[(\text{necrotic tissue length}/\text{total linear length}) \times 100]$) was calculated for each colony that maintained the upright position. Additionally, a Wilcoxon signed-rank statistical test (Wilcoxon, 1945) was used to detect differences in percentage of necrosis between large and small studied gorgonian sizes. Statistical analyses were carried out with R (RCore Team, 2018) by means of the R Studio software (RStudio Team, 2016) using the 'ggplot2' package (Wickham, 2016), the 'lme4' package (Bates, Mächler, Bolker, & Walker, 2015) for the linear mixed model and the general linear mixed model, and the 'gam' package (Hastie & Tibshirani, 1987) for the GAM model. The 'AICcmodavg' package (Mazerolle, 2019) was also used in the model comparison.

3 | RESULTS

3.1 | Landing efficiency

Depth, cobble type, and gorgonian size affected the landing success of transplants (Anova Type II of the binomial model; Depth: $\chi^2 = 16.045$; $df = 1$; $P < 0.001$; Cobble type: $\chi^2 = 29.463$; $df = 2$; $P < 0.001$ Gorgonian size: $\chi^2 = 22.314$; $df = 1$; $P < 0.001$. Figure 2 and Supplementary Material 2). For all the cobble types tested, and regardless of the gorgonian size, the probability of landing upright increased with depth (Figure 2). Transplants with small artificial cobbles displayed the highest probabilities of successful landing at all depths (close to 100% of upright landing; Figure 2), followed by large artificial cobbles and natural cobbles. According to the gorgonian size, large gorgonian colonies showed a higher probability of upright landing than small colonies (Figure 2). Regarding the prediction model, a 100% success of gorgonian landing in upright position at 80 m depth (i.e. on the continental shelf), for all the cobble types was forecast (Figure 3 and Supplementary Material 3). Focusing only on natural cobbles, there was a strong positive relationship (Spearman's $r = 0.80$; $P = 0.004$; $n = 10$) between the landing success of natural cobbles (% of upright landing) and their SI (Figure 4). On the contrary, there was no correlation between the weight of the cobbles and their probability of landing success.

Regarding the dispersion area reached by the gorgonian transplants on the sea bottom, among all the models tested the one

FIGURE 2 Probability of transplants landing in upright position according to depth, cobble type, and gorgonian size. Dots show real observations with an interval confidence of 95% and lines correspond to the predicted values of the GLM model for binomial data. NC = natural cobbles; SAC = small artificial cobbles; LAC = large artificial cobbles ($n = 120$)

FIGURE 3 Predicting model of probability of transplants landing in upright position according to depth and cobble type, using a logistic general linear model for binomial data. NC = natural cobbles; SAC = small artificial cobbles; LAC = large artificial cobbles. Colour shadows correspond to 95% intervals confidence corresponding to the general linear model

providing the best fit was a GLM with γ -distribution ($AICc = 73.9$; Figure 5 and Supplementary Materials 4 and 5). The model showed that depth and cobble type significantly influenced the dispersal area reached by transplants (ANOVA Type II; Depth: $LR \chi^2 = 111.657$, $df = 1$, $P < 0.001$; Cobble type: $LR \chi^2 = 22.96$, $df = 2$; $P < 0.001$), predicting an increase in the dispersal area with depth (Figure 5). Natural cobbles showed the largest dispersal area at 80 m depth ($60.8 \pm 20.6 \text{ m}^2$, mean $\pm$ SD), followed by small artificial ($47.6 \pm 16.3 \text{ m}^2$) and large artificial cobbles ($34.3 \pm 11.6 \text{ m}^2$).

3.2 | Monitoring of transplants

All the cobbles located at 30 m depth remained in an upright position during the first month. During the second and third months, all the natural cobbles (100%) and almost all the small artificial cobbles

FIGURE 4 Scatter plot showing the correlation between percentage of upright landing and the sphericity index of natural cobbles ($n = 10$)

(90%) remained in an upright position, contrasting with the lower percentage (60%) of large artificial cobbles that maintained an upright position (Figure 6). The size of the gorgonian colony did not influence the overturning of the transplants since statistical differences were not detected in the position of the transplants at the end of the monitoring according to gorgonian size ($W = 3.5$, $P = 0.814$). The mean necrosis percentage of the gorgonian transplants at 30 m depth that remained in an upright position during all the monitoring period was very low and not statistically different between gorgonian sizes ($W = 58$, $df = 1$, $P = 0.281$), being $3.65 \pm 6.4\%$ in large colonies and $5.63 \pm 5.7\%$ in small colonies. In the most affected colony, the necrotic tissue represented 17.6% of the total ramification length (Figure 7).

4 | DISCUSSION

The present results have shown that the 'badminton method' can be a cost-effective restoration method to potentially restore cold-water coral gardens over large scales.

FIGURE 5 Model predictions of the dispersion area reached by the gorgonian transplants according to cobble type at different depths, using a general linear model with γ -distribution. Dots show real observations and lines with shadow correspond to the predictions of the model and its corresponding 95% intervals confidence. NC = natural cobbles; SAC = small artificial cobbles; LAC = large artificial cobbles ($n = 120$)

FIGURE 6 Proportion of cobbles that maintained the upright position at 30 m depth according to cobble type during 3 months. NC = natural cobbles; SAC = small artificial cobbles; LAC = large artificial cobbles ($n = 30$)

FIGURE 7 Percentage of necrosis in gorgonian transplants that maintained the upright position at 30 m depth during 3 months (12 small colonies and 13 large colonies)

The probability of successful landing of transplants increased with depth for the three cobble types tested, and by using gorgonian colonies of large size (Figure 2). Gorgonian colonies attached to cobbles act similar to a badminton shuttlecock, slowing down the fall and forcing an upright landing of the transplants due to the hydrodynamic resistance of the highly branched surface of the gorgonian. Consequently, by using large instead of small colonies, this effect is enhanced. Regarding transplant support types, the small artificial cobbles were the most effective at all depths, but all the three support types showed high probabilities of successful landing at 30 m depth, if large colonies were attached (>90% of upright landing; Figure 2). Accordingly, the model predicted a 100% landing success for all the cobble types returned to the continental shelf (80 m depth; Figure 3).

Once on the sea floor, remaining in an upward position is crucial for the survivorship of the gorgonian transplants. The size of the gorgonian colony did not influence the overturning of the transplants whereas the cobble type did. Natural and small artificial cobbles successfully maintained the upright position after 3 months at 30 m depth (100% and 90% maintained the upright position, respectively), where hydrodynamic conditions are even stronger than in deeper areas on the continental shelf (Garrahou, Ballesteros, & Zabala, 2002). In contrast, large artificial cobbles were less stable (60% maintained the upright position) and more easily overturned due to their semi-spherical shape. There were no differences in the amount of necrotic tissue between large and small transplanted colonies that remained upright over the 3 months, suggesting that all cobbles were sufficiently heavy to hold the transplanted colonies, without causing any movement that could result in abrasion of the tissue.

Based on these results about the landing efficiency and the capability of the transplants to maintain an upright position once on the sea floor, natural cobbles with large gorgonians attached are considered as the best option to ensure the success of this restoration method. Using large colony transplants will be further advantageous, since they have been shown to suffer less natural mortality after transplantation (Brooke et al., 2006), and have greater capacity to regenerate from injuries, being more resilient to further impacts (Fava, Bavestrello, Valisano, & Cerrano, 2010; Henry & Hart, 2005). Likewise, reintroduction of large gorgonians will foster the recovery of the three-dimensional structure of the coral gardens, and their habitat-forming functions, providing habitats for a large number of associated species (Geist & Hawkins, 2016; Horoszkowski-Fridman, Brêthes, Rahmani, & Rinkevich, 2015). Indeed, the recovery of ecosystem functioning is by definition one of the main goals of ecological restoration (Society for Ecological Restoration International Science & Policy Working Group, 2004).

By using natural cobbles, no artificial material is introduced to the environment. This is in agreement with the recommendation of using natural substratum, as highlighted for shallow water gorgonian transplant experiments, in which the ineffectiveness of using man-made devices (i.e. PVC-clamps and PVC-racks) was identified (Weinberg, 1979). However, when selecting natural cobbles to be used for the restoration, flat cobbles should be avoided. Indeed, our results showed a strong positive relationship between the sphericity of the

natural cobbles and their probability of landing upwards, with the flat-test cobbles performing worse (i.e. a smaller percentage of landings in upright position) than the rounder ones (Figure 4). During the fall, if the transplants were falling upside-down (i.e. cobbles would land overturned), even large gorgonians did not provide enough hydrodynamic resistance to reverse the trend and overturn the flatter cobbles.

The variability in shape and weight of natural cobbles resulted in the largest predicted dispersion area ($60.8 \pm 20.6 \text{ m}^2$) of gorgonian transplants on the continental shelf (80 m depth; Figure 5). This could reduce the chance of two or more transplants landing on top of each other, enabling the restoration of large areas in the continental shelf. Restoring large areas has already been successful in tropical shallow environments, where coral reef restoration has been performed at scales from 10 m^2 to several hectares (Edwards & Gomez, 2007). One of the main goals of ecological restoration is to restore a natural range of ecosystem composition, structure and dynamics (Falk et al., 2006; Society for Ecological Restoration International Science & Policy Working Group, 2004). In this sense, and taking into account that 60 m^2 would be the mean area reached on the continental shelf by 10 gorgonian transplants dropped from the surface, we should consider performing multiple drops at the same site to achieve gorgonian densities similar to natural populations of *E. cavolini* dwelling on the Mediterranean continental shelf (on average $2.8 \pm 4.3 \text{ colonies m}^{-2}$, with some high density patches above $25 \text{ colonies m}^{-2}$) (Dominguez-Carri, 2018).

Concerning the survival of the transplants, the degree of necrosis observed after the 3 months of monitoring (<20% of necrosis in the most affected colonies and <6% on average, Figure 7) was similar to values recorded for other Mediterranean gorgonian species in natural conditions. For instance, the percentage of necrotic tissue among *Paramuricea clavata* colonies ranged from 0 to 22% with a mean of 10% (Coma et al., 2004; Linares, Coma, Garrabou, et al., 2008), and a maximum of 24% of necrotic tissue was reported among *Eunicella singularis* colonies, with a mean of 5% (Linares, Coma, Garrabou, et al., 2008). Water turbulence (influenced by strong wave action), high irradiance, and algal competition can compromise the survival of gorgonian transplants in shallow environments (Linares, Coma, & Zabala, 2008; Weinberg, 1979). During the monitoring period, these stressor drivers could have affected the transplants settled in much shallower water (30 m depth) than the natural depth range of the species in the study area (i.e. 60–120 m depth, Dominguez-Carri, 2018; Gili et al., 2011). Even so, the amount of necrosis detected after the 3 months of monitoring was still low. The overall efficiency of the 'badminton method' is in line with the results obtained from other coral and gorgonian transplantation experiments. A review of 40 studies about hexacoral restoration actions reported a mean annual survival of 60% with a range of 6–98% (Montero-Serra et al., 2018). For Mediterranean gorgonian species, such as *E. singularis*, *Eunicella verrucosa*, *P. clavata*, and *Corallium rubrum*, the mean annual survival observed was 48% (ranging between 30 and 99%) (Fava et al., 2010; Linares, Coma, & Zabala, 2008; Montero-Serra et al., 2018). The limited information from cold-water coral restoration experiments showed that during the first year, a mean survivorship

of the coral transplants of around 50–60% (Boch et al., 2019; Brooke et al., 2006).

Due to cold-water coral ecosystems' role as biodiversity hotspots (Baillon, Hamel, Wareham, & Mercier, 2012; Henry & Roberts, 2007), awareness about the need and the importance of their protection and restoration is increasing worldwide (Davies et al., 2007; WWF/IUCN, 2004). First attempts towards the assisted regeneration (active ecological restoration) of these ecosystems demonstrated the high survival of transplants for reef-forming cold-water corals (*Oculina varicosa* [Brooke et al., 2006] and *Lophelia pertusa* [Dahl, 2013; Jonsson et al., 2015]) and for cold-water gorgonians (*E. cavolini*) (Montseny et al., 2019). However, technical and logistical difficulties of working below the limit of scuba diving necessitate the use of underwater technology. Such technological requirements increase the costs of restoration actions by two or three orders of magnitude compared to shallow areas (Van Dover et al., 2014). Moreover, cold-water coral restoration actions performed to date have been based on transplantation of coral fragments on artificial structures, which significantly limit the area that can be restored (Brooke et al., 2006; Dahl, 2013; Montseny et al., 2019). Thus, in order to increase the scale of restoration actions, many artificial structures would be needed, further increasing the economic cost and the technical constraints. In this sense, and given that the main threats impacting natural habitats occur on large scales (Halpern et al., 2008), it is a foremost challenge to develop effective methods for upscaling ecological restoration actions (Aronson & Alexander, 2013; Perring, Erickson, & Brancalion, 2018). Indeed, a mismatch between the scale at which ecological restoration can currently be done and the scale at which major impacts act has been highlighted for tropical shallow coral reefs (Edwards & Gomez, 2007; Montoya Maya, Smit, Burt, & Frias-Torres, 2016; Pollock et al., 2017). Regarding this aspect, the 'badminton method' allows for restoration of high number of gorgonians colonies over extended areas without the need for high-cost underwater technology. Moreover, by using bycatch gorgonians, no additional impact to healthy donor coral gardens will be generated, while a viable output for those gorgonians already fished is provided. Finally, directly involving professional fishers in restoration actions, will also increase the awareness of local society about the need for the protection of cold-water coral gardens and would facilitate the application of this methodology in an extensive manner, which is crucial for the restoration success (Gobster & Hull, 2000; Yap, 2000).

The current and future perspectives about the degradation of continental shelves (Halpern et al., 2008) and the urgency for conservation and restoration of their benthic communities (Borja, 2005) supports the development of new methodologies like that presented in this work. The present study shows that the 'badminton method' can be a reliable cost-effective and large-scale restoration method to assist the recovery of cold-water coral gardens located beyond the limit of scuba depth. It should be highlighted that apart from being a valid technique for continental shelves and potentially for deep environments, it could also be applied to shallower mesophotic coral ecosystems. While the 'badminton method' in this study has been demonstrated to be successful for sandy or gravel horizontal bottoms,

further studies should explore its applicability to other bottom types, like those in upper-slope habitats or cold-water coral reefs habitats.

The present study is a first evaluation of the 'badminton method' that needs now to be followed by a real application in areas of the continental shelf in order to corroborate the long-term survival success predicted by the present results. Furthermore, the limited sample size, arising from the difficulties of working at depths (Claus & Hoog, 2002), results in model predictions with large margin errors constraining broader conclusions of this study. These limitations will be assessed and reduced based on future monitoring of gorgonians transplanted on the continental shelf; the success of ecological restoration, however, should only be generally demonstrable within 10–50 years (Jackson, Lopoukhine, & Hilyard, 1995; Suding, 2011). A general reduction of fishing impacts, together with effective protection mechanisms for cold-water coral gardens are greatly preferable to avoid the need for potentially expensive and long-term restoration projects (Possingham et al., 2015).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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Uncorrected Proofs