

# 1 Coral reef restoration efforts in Latin American countries and territories

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## 39 **Abstract**

40 Coral reefs worldwide are degrading due to climate change, overfishing, pollution, coastal  
41 development, bleaching and diseases. In areas where natural recovery is negligible or protection  
42 through management interventions insufficient, active restoration becomes critical. The Reef Futures  
43 symposium in 2018 brought together over 400 reef restoration experts, businesses, and civil  
44 organizations, and galvanized them to save coral reefs through restoration or identify alternative  
45 solutions. The symposium highlighted that solutions and discoveries from long-term and ongoing coral  
46 reef restoration projects in Spanish-speaking countries in the Caribbean and Eastern Tropical Pacific  
47 were not well known internationally. Therefore, a meeting of scientists and practitioners working in  
48 these locations was held to compile the data on the extent of coral reef restoration efforts, advances  
49 and challenges. Here, we present unpublished data from 12 coral reef restoration case studies from  
50 five Latin American countries, describe their motivations and techniques used, and provide estimates  
51 on total annual project cost per unit area of reef intervened, spatial extent as well as project duration.  
52 We found that most projects used direct transplantation, the coral gardening method, micro-  
53 fragmentation or larval propagation, and aimed to optimize or scale-up restoration approaches (51%)  
54 or provide alternative, sustainable livelihood opportunities (15%) followed by promoting coral reef  
55 conservation stewardship and re-establishing a self-sustaining, functioning reef ecosystem (both  
56 13%). Reasons for restoring coral reefs were mainly biotic and experimental (both 42%), followed by  
57 idealistic and pragmatic motivations (both 8%). The median annual total cost from all projects was  
58 \$93,000 USD (range: \$10,000 USD - \$331,802 USD) (2018 dollars) and intervened a median spatial  
59 area of 1 ha (range: 0.06 ha - 8.39 ha). The median project duration was 3 years; however, projects  
60 have lasted up to 17 years. Project feasibility was high with a median of 0.7 (range: 0.5 - 0.8). This  
61 study closes the knowledge gap between academia and practitioners and overcomes the language  
62 barrier by providing the first comprehensive compilation of data from ongoing coral reef restoration  
63 efforts in Latin America.

## 64 **Introduction**

65 Active restoration, the process of assisting the recovery of an ecosystem that has been degraded,  
66 damaged, or destroyed [1], may be increasingly necessary on coral reefs, once it has been determined  
67 that the natural recovery of corals is hindered [2]. The goal of any restoration action is to eventually  
68 establish self-sustaining, sexually reproducing populations with enough genetic variation enabling  
69 them to adapt to a changing environment [3-5].

70 Coral reef restoration may play a particularly important role where coral species are threatened with  
71 extinction. The Caribbean Elkhorn coral, *Acropora palmata*, and Staghorn coral, *A. cervicornis*, were  
72 once widely distributed and among the major reef-building species in the region [6]. Both species are  
73 now listed as Critically Endangered on the International Union for Conservation of Nature (IUCN) Red  
74 List [7] as a result of major losses in cover of both species throughout the Caribbean since the 1970s  
75 [8]. Management programmes have not aided in the recovery of *A. palmata* [9]. In this context, active  
76 restoration of these species is essential to recover their ecosystem functions in the Caribbean region.

77 Several techniques are used for the restoration of coral reefs. The most common techniques are based  
78 on asexual methods such as direct transplantation, coral gardening, and micro-fragmentation [10]. An  
79 alternative technique, larval propagation, is based on the collection of gametes and the consequent  
80 culturing of embryos and larvae, after which the coral spat are either grown in *ex situ* aquaria to larger-  
81 sized colonies or are outplanted onto degraded reefs at approximately one month old [11]. While the  
82 techniques used to restore coral reefs are reviewed elsewhere (e.g. [10, 12-14]), here we focus on  
83 direct transplantation, coral gardening, micro-fragmentation, and larval propagation as the  
84 techniques most-commonly employed by the case studies in the study area. One of the oldest  
85 techniques used in coral reef restoration is direct transplantation of corals [15], which involves the  
86 harvesting of coral colonies from a donor site and their immediate transplantation to a restoration  
87 site or re-attaching colonies that have been dislodged by a ship grounding, storm or hurricane [16].  
88 The coral gardening approach was developed to scale-up restoration while reducing the stress on

89 donor colonies. Fragments of corals are harvested from donor colonies, grown in nurseries to a  
90 threshold size [17] before being transplanted onto a degraded reef [18, 19]. Nurseries can be ocean-  
91 based (*in situ*) or land-based (*ex situ*). *In situ* nurseries are typically located at well-lit sites safe from  
92 predation, storm surges, and wave energy, and are regularly maintained and cleaned by physical  
93 removal of algal growth [20]. However, strategic siting of ocean nurseries can promote the  
94 recruitment of fish assemblages that eat biofouling, thus may significantly reduce person-hours spent  
95 in nursery cleaning [21]. *In situ* nurseries can have many shapes and sizes. For example, they can  
96 consist of floating mid-water structures built using ropes, mesh or cages [21-24], structures placed on  
97 concrete, tables or frames [25], PVC 'trees' [26], PVC grids or dead coral bommies [27]. *Ex situ*  
98 nurseries typically use flow-through large aquaria or raceways, and require continuous access to  
99 electricity, water quality monitoring, and control of temperature and light availability [28]. Micro-  
100 fragmentation is an approach especially useful for slow-growing massive corals. This technique  
101 involves the fragmentation of parts of a massive coral donor to yield multiple  $\sim 1 \text{ cm}^2$  fragments. The  
102 fragments are placed close to each other on either artificial substrates or on the surface of dead coral  
103 colonies. The micro-fragments, as they recognize neighbouring fragments as kin, grow towards each  
104 other and fuse [29]. Ideally, they are outplanted to the degraded reef at a size of  $\sim 6 \text{ cm}^2$  [29, 30]. Larval  
105 propagation involves the breeding of corals from eggs and sperm. Studies describing this technique  
106 typically report the use of raceways with seawater flow-through systems where coral spawn is  
107 collected from the wild, fertilization is assisted, embryos are cultured to larvae, which are settled onto  
108 substrates and then transported and seeded onto a degraded coral reef [31-33]. This process has also  
109 been referred to as larval enhancement, sexual propagation, sexual coral cultivation or larval  
110 reseedling [12]. As an emerging larval propagation technique, larval restoration concentrates coral  
111 larvae over enhancement plots on the degraded reef to facilitate coral larvae settlement directly to  
112 the substrate, without the need of laboratory facilities [34]. The main advantages of the larval  
113 propagation techniques are that they increase the genetic diversity among restored coral populations  
114 thus enabling increased rates of adaptation and improved resilience in the context of climate change

115 [35], and they have the potential to be used over large scales while reducing the cost [31]. Also, they  
116 do not cause damage to the parent colonies.

117 While efforts in the USA, Australia or places where European scientists conduct their research are well  
118 described in the published literature and disseminated at conferences, there is a paucity of  
119 documentation on coral reef restoration projects carried out by practitioners in the Caribbean and  
120 Eastern Tropical Pacific. Reasons for this lack of exchange may be the language barrier, lack of interest  
121 in knowledge transfer between higher and lower income countries or cultural differences as well as  
122 lack of funding. In 2018, the Reef Futures symposium was held in the Florida Keys, USA and attended  
123 by over 400 delegates. The aim of this international meeting was to 'bring together experts from  
124 around the world to share the latest science and techniques for coral reef restoration while kicking off  
125 a global effort to dramatically scale-up the impact and reach of restoration as a major tool for coral  
126 reef conservation and management'. The conference was organized by the Coral Restoration  
127 Consortium, which is 'a community of practice comprised of scientists, managers, coral restoration  
128 practitioners, and educators dedicated to enabling coral reef ecosystems to survive the 21<sup>st</sup> century  
129 and beyond' [36]. Within the Reef Futures conference, we convened a meeting of scientists and  
130 practitioners involved in active coral reef restoration in the Latin- and Centro-American Caribbean as  
131 well as the Eastern Tropical Pacific to fill the knowledge gap between academia and practitioners in  
132 the region and overcome the language barriers in coral reef restoration. Here, we showcase the  
133 advances and share the lessons learned from 12 restoration case studies from the Caribbean and  
134 Eastern Tropical Pacific. We provide a comprehensive compilation of unpublished data from coral reef  
135 restoration efforts where we outline the techniques that were employed, the motivations and  
136 objectives of each project, total project cost per unit area per year, spatial extent of intervention, and  
137 project duration. This work provides the most complete data set on total project cost and feasibility  
138 of coral reef restoration from practical cases that may guide decisions required to establish new  
139 restoration projects in the future.

## 140 **Approach**

### 141 *Data collection*

142 The co-authors of this work contributed data and descriptions of their restoration projects which  
143 constitute the case studies used here. The coral reef restoration projects were carried out in Latin  
144 American countries and territories in the Caribbean and Eastern Tropical Pacific (**Fig. 1**). The data  
145 obtained included estimates on total annual project cost, spatial extent of area intervened, project  
146 duration, and an estimate on the project reaching specific objectives within a fixed period of time. The  
147 motivations for each restoration project were adopted from [10, 37, 38] and classified as biotic,  
148 experimental, idealistic, legislative, and pragmatic (**Table 1**).

149 **Table 1:** Five motivation categories for carrying out coral reef restoration projects and examples.

| Motivation category | Examples   |
|---------------------|--|
| Biotic              | Biodiversity enhancement (e.g., native species, habitat creation, ecosystem connectivity, ecological resilience)     |
| Experimental        | Improve restoration approaches, technologies, and methods. Answer ecologically-based research questions              |
| Idealistic          | Cultural reasons (e.g., recreation, tourism, medicinal/ceremonial substances, spiritual importance, aesthetic value) |
|                     | Social reasons (e.g., community involvement, job creation, nature education, environmental outreach)                 |
|                     | Political reasons (e.g., raising environmental profile)  |
| Legislative         | Restoration after environmental impact (e.g., ship-grounding, mining, oil spill, hurricane damage)                   |
|                     | Biodiversity offset (e.g., threatened species, threatened ecological communities)                                    |
| Pragmatic           | Enhance ecosystem services (e.g., fisheries production)  |
|                     | Enhance ecosystem services (e.g., water quality improvement, pollution prevention)                                   |
|                     | Enhance ecosystem services (e.g., coastal protection, erosion control, bank stabilisation)                           |
|                     | Enhance ecosystem services (e.g., carbon sequestration, carbon offsets)  |

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151 The objectives of coral reef restoration projects can be highly diverse and dependent on the specific  
152 project as well as its location. In this study, the restoration practitioners were asked to provide the  
153 objectives for their restoration projects, which were specific, measurable, achievable, repeatable and  
154 time-bound (SMART; [3]). We modified the six primary objectives observed by Hein et al. [39] into the  
155 following categories: 1) enhance ecosystem services for the future; 2) optimize/scale-up restoration  
156 approaches; 3) promote coral reef conservation stewardship; 4) provide alternative, sustainable  
157 livelihood opportunities; 5) reduce coral population declines and ecosystem degradation; and 6) re-  
158 establish a self-sustaining, functioning reef ecosystem.

159 The total estimated project cost includes both capital and operating costs. Capital costs are those used  
160 for planning, land acquisition, construction, and financing [40]. These may also include costs for  
161 laboratory/infrastructure, boats and dive equipment. Operating costs are those used for maintenance,  
162 monitoring, equipment repair and replacement [40] and may include salaries, housing for  
163 scientific/implementation teams, air for SCUBA tanks, gasoline for boat engines, and replacement of  
164 computers. Coral reef practitioners were asked to estimate the total cost for restoration interventions  
165 based on the guidelines for standardised reporting of costs for management interventions for  
166 biodiversity conservation [41] and are provided as United States Dollars (USD) per hectare of coral  
167 reef intervened per year in 2018 USD.

168 The project spatial extent is the coral reef area intervened by the restoration project and is reported  
169 in hectares. Spatial extent is not provided for each project since not all restoration case studies have  
170 an objective to increase the area of restored habitat. For instance, some projects are aimed at  
171 developing new restoration techniques, using coral nurseries as a tool to stimulate public awareness  
172 and engagement, for educational purposes, or as a tourist attraction.

173 The project duration is the time during which the restoration project has existed until the present, or  
174 the time during which the restoration cost was budgeted for and is provided in years. All projects  
175 described here are ongoing and active throughout 2019.

176 The feasibility is the likelihood that each specific project objective can be reached successfully with  
177 the interventions at hand and within the outlined project duration. It is ideally measured as the  
178 likelihood of success in returning the ecosystem function and resilience of an ecosystem through  
179 restoration [42]. This overall restoration project feasibility is rarely reported in the published literature  
180 because a standardised method to measure restoration success is largely missing [40]. Here,  
181 restoration practitioners estimated the feasibility of the restoration interventions they employed to  
182 achieve their specific project objectives. Feasibility is given as a ratio between 0 and 1 and can be  
183 interpreted as the likelihood of success to reach a specific objective within the duration of the  
184 restoration project. Practitioners provided a minimum, maximum and the best guess for the project  
185 feasibility.

## 186 **Results**

187 Data from a total of 12 coral reef restoration projects carried out by practitioners in the Spanish-  
188 speaking Caribbean and Eastern Tropical Pacific were compiled and are summarised in **Table 2**. The  
189 supplementary material contains more detailed information about each restoration case study.  
190 Information was gathered from Colombia (Alianza Coralina Taganga, Corales de Paz, and ECOMARES),  
191 Costa Rica (Raising Coral Costa Rica), the Dominican Republic (FUNDEMAR, the Iberostar Group, and  
192 Fundación Grupo Puntacana), Mexico (Oceanus A.C., CORALIUM at Universidad Nacional Autónoma  
193 de México, and the Iberostar & CINVESTAV Group), and Puerto Rico (Sociedad Ambiente Marino)  
194 (**Figure 1**). Note that the Fundación Grupo Puntacana has two restoration programs of which one is  
195 focused on coral gardening (Program 1) and one is directed towards micro-fragmentation (Program  
196 2). These were treated as independent projects for analytical purposes. The restoration projects use  
197 techniques that include direct transplantation, coral gardening, micro-fragmentation, and larval  
198 propagation (**Figure 2**; Supplementary information **Table S1**).



199 **Table 2:** Summary of the 12 restoration projects in the Caribbean and Eastern Tropical Pacific. Cost values are given in 2018 USD. More detailed information  
 200 can be found in the supplementary material. Abbreviations: Fundación Dominicana de Estudios Marinos, Inc. (FUNDEMAR), Fundación Grupo Puntacana  
 201 (FGPC), and Sociedad Ambiente Marino (SAM).

| Country, Location, Organization   | Technique employed (type of nursery)   | Targeted coral species   | Motivations  | Specific project objectives  | Strategy for outplanting  | Spatial extent of project   | Estimated project budget and funding bodies/partners   | Estimated project feasibility                        |
|---|--|--|--|--|---|---|--|--|
| <b>Implemented and in progress as of 2019</b>                               |  |  |  |  |   |   |  |  |
| Colombia, Taganga, Caribbean Sea, Alianza Coralina Taganga                  | A floating mid-water nursery built of PVC tubes is located 5 m below the water surface and anchored to the sandy bottom at 13 m depth. Coral fragments are produced by micro-fragmentation of donor colonies, which are then attached to cement cookies and outplanted once they reach a diameter of 7 cm. Each cement cookie is connected via a plastic screw to a mesh frame in the coral nursery with a carrying capacity of 50 – 80 cookies per frame. Corals of opportunity are presently used. | <i>Montastraea cavernosa</i> ;<br><i>Porites porites</i> ;<br><i>Millepora</i> sp.   | The primary motivation is idealistic following social reasons such as community education and engagement. The secondary motivation is experimental i.e., to improve management and develop standardized restoration protocols. | 1) to develop a training centre for the sustainable use of marine resources and ecological restoration; 2) to establish a community-based coral reef monitoring system for Taganga Bay and coral nurseries therein with the possible expansion of monitoring to other areas; 3) to develop a management plan for Taganga Bay as a marine reserve, which is governed by the local community; and 4) to create a financed organization, which aims to facilitate long-term ecological reef restoration and research in Taganga Bay | Corals grown in the mid-water nursery will be outplanted by drilling holes in the natural substrate with a pneumatic drill and inserting the plastic nails of the cement cookies carrying the coral fragments into the holes (supported by epoxy glue where necessary). All outplanted corals at the restoration site will be monitored at least once per month while they reattach to the natural substrate. | The spatial extent of the project is currently a matter of negotiation that depends on the capacity to recruit coral gardeners from the local community and to obtain a permit to carry out the ecological restoration work in Taganga Bay. | An estimated budget for the project is \$500,000 USD over the next two years. Forty percent of this budget is self-funded by local stakeholders to accelerate the capacity of coral growth and maintenance of coral outplanting through local capacity building. A large proportion of the estimated project budget will be directed to activities such as education, community engagement and training while a minor part will be focused on growing and outplanting corals to the restoration site. Members from the local community are trained as coral gardeners to identify corals of opportunity, carry out coral micro-fragmentation and maintain the nursery. | best guess = 0.5;<br>minimum = 0.2;<br>maximum = 0.9 |
| Colombia, San Andres and Providencia Islands, Caribbean Sea, Corales de Paz | The project employs the coral gardening technique. Rope nurseries are floating at 4 to 6 m below the water surface (Fig. 2a). Micro-fragmentation is also  | <i>Acropora palmata</i> ; <i>A. cervicornis</i> ;<br><i>Porites porites</i> ;<br><i>Madracis decactis</i> ;<br><i>Pseudodiploria</i> | The primary project motivation is biotic i.e., to enhance coral reef biodiversity, while the secondary motivation is pragmatic i.e., to enhance the ecosystem  | 1) to generate an annual stock of > 5,000 coral fragments from four reef-building species per island; 2) to transplant 5,000 coral colonies per ha <sup>-1</sup> yr <sup>-1</sup> per island from year two of the project, for a total of 30,000 coral transplants over six  | Nursery-grown corals as well as micro-fragments will be outplanted to the reef using a unique mix of marine cement and a colloid adjuvant to improve fluidity and   | The total spatial extent is six hectares (area of outplant) by year four distributed over three hectares at each of the two islands.  | The total estimated budget is \$900,000 USD resulting in an annual expenditure of \$37,500 USD ha <sup>-1</sup> yr <sup>-1</sup> . Partners include the Secretary of Agriculture and Fisheries from the Government of the Archipelago of San Andrés,   | best guess = 0.6;<br>minimum = 0.5;<br>maximum = 0.9 |

being employed during the outplanting phase.

*clivosa*; *P. astreoides*; *Millepora complanata*

services of fisheries, tourism and coastal protection by the local coral reefs.

hectares in three years; 3) to achieve a 25% increase in selected coral reef health indicators (i.e., live coral cover, coral settlement, fish biomass, and rugosity) at the intervened sites; 4) to design and implement an effective system of protection and restoration of intervened reef areas that encourages conservation and contributes to the sustainability of benefits derived from these reefs together with relevant social actors; and 5) to quantify the ecosystem services of intervened reef areas in current and future scenarios of intervention, variability and climate change

reduce runoff. Outplanting density will be 5,000 individuals per ha of reef.

Providencia and Santa Catalina, the provincial environmental authority CORALINA, Conservation International Colombia, and the NGO Corales de Paz. Both islands are within the Seaflower Biosphere Reserve in the Colombian Caribbean. The first phase of the project was financed by all participating organizations with support from MasBosques and BanCO2.

|   |  |   |  |  |   |   |  |  |
|---|--|---|--|--|---|---|--|--|
| Costa Rica, Golfo Dulce, Eastern Tropical Pacific, Raising Coral Costa Rica | The project employs the techniques coral gardening and micro-fragmentation. Coral fragments are often collected as fragments of opportunity and are grown in tree and rope nurseries, after which they are outplanted to the restoration site (Fig. 2f). | <i>Pocillopora</i> sp.; <i>Porites evermanni</i> ; <i>P. lobate</i> ; <i>Pavona gigantea</i> ; <i>Pavona frondifera</i> ; <i>Psammocora</i> sp. | The primary motivation of the project is experimental with the rationale to improve coral propagation techniques for growing corals in the Eastern Tropical Pacific, with an emphasis on answering questions of ecological concern. The secondary motivation is biotic i.e., to enhance biodiversity, ecosystem connectivity, and ecological resilience. | 1) to define the best coral propagation and restoration techniques; 2) to establish a coral restoration program in Costa Rica; 3) to facilitate coral reef research to improve restoration work; and 4) to integrate local communities into coral restoration projects | Branching corals grown in the nursery are outplanted onto the substrate with cable ties attached to large nails. Future endeavours will attach corals grown on ropes in rope-nurseries directly to the substrate without separating them from the ropes. Massive and encrusting corals, which are grown on ceramic plugs, are outplanted by drilling holes into the substrate and inserting the stem of the plug with a small amount of marine epoxy or cement. | The project aims to restore 10 reef patches of 200-500 m <sup>2</sup> each within the next three years equalling a maximum intervened area of 0.5 ha. | The total project cost over the last 2.5 years was \$120,000 USD. If in kind support (such as accommodation, university technical support, volunteer time, etc.) is included, these costs would be 100% higher, i.e., a total of \$240,000 USD. The annual project budget was \$35,000 USD for 2018, which was mostly composed of salaries (\$15,000 USD) and logistics such as travel and boat rental (\$15,000 USD). The remaining \$5,000 were needed for material and consumables. The project is mainly financed by private donations and Raising Coral Costa Rica is currently initiating a fundraising campaign call to restore several thousand corals for Costa Rica and to scale-up coral propagation and restoration efforts. | best guess = 0.8; minimum = 0.6; maximum = 0.9 |
| Dominican Republic,   | The techniques coral gardening (rope and steel   | <i>Acropora cervicornis</i> ;   | The primary motivation of the project is biotic  | 1) to propagate coral tissue of the endangered <i>A. cervicornis</i> using   | Corals grown in eight underwater nurseries  | FUNDEMAR's restoration project  | FUNDEMAR is a largely self-sustainable organization that has   | best guess = 0.7; minimum = 0.4;               |

|  |  |  |   |   |   |   |  |  |
|--|--|--|---|---|---|---|--|--|
| Bayahibe, Caribbean Sea, FUNDEMAR                                | rod nurseries ( <b>Fig. 2b</b> ) and larval propagation (seeding coral recruits after cultivation using <i>in situ</i> SECORE Int.-designed floating pools ( <b>Fig. 2c</b> ) and <i>ex situ</i> in a wet lab) are used to restore local coral populations.  | <i>A. palmata</i> ; <i>Colpophyllia natans</i> ; <i>Diploria labyrinthiformis</i> ; <i>Orbicella annularis</i> ; <i>O. faveolata</i> ;   | with the rationale of biodiversity enhancement. The secondary motivation is legislative focused on restoration after environmental impact and as a biodiversity offset. However, the project has also idealistic motivations for cultural, social and political reasons.  | the genetically diverse coral nurseries; 2) to enhance coral populations' genetic diversity and resilience to environmental changes by outplanting substrates (either SECORE's cement or ceramic substrates or FUNDEMAR's cement "cookies") with settled coral recruits.  | (holding more than 3 km of tissue) are outplanted with nails, cable ties and epoxy glue techniques. FUNDEMAR has already carried out coral outplanting at 12 restoration sites ( <b>Table S3</b> , supplementary material). The project is monitoring two spawning sites used to deliver the spawning stocks for rearing coral larvae in an <i>ex situ</i> facility ( <b>Table S2</b> , supplementary material). Corals reared by larval propagation settle on hand-made cement or ceramic substrates which are nailed or seeded on the reef. | aims to intervene on at least 0.5 hectares of degraded coral reef per year on a restoration schedule of one coral colony per square meter, transplanting around 2,000 <i>A. cervicornis</i> coral fragments of around 20-30 cm in diameter and seeding 2,000 recruit substrates (from 3-5 different species). | developed strategic alliances with private and public national and international institutions and with financial support for implementation of new projects. The total project cost per year is around \$51,800 USD which includes costs for maintenance, staff salaries, boats, and keeping up the facility but excludes in-kind support from volunteers. Part of this funding (\$18,400 USD per year) comes from the local, national and international alliances that FUNDEMAR has established. The coral reef restoration project has been financed by two grants and alliances with other organizations carrying out coral reef restoration.                       | maximum = 0.9                                  |
| Dominican Republic, Bayahibe, Caribbean Sea, The Iberostar Group | The Iberostar Group uses the coral gardening technique to restore coral reefs and is currently in charge of two coral nurseries at two locations in the Dominican Republic. One of the nurseries is an <i>in situ</i> nursery and the other one is an <i>in situ</i> nursery connected to a land-based facility for research and to evaluate the genetic diversity of corals in the nursery. | <i>Acropora cervicornis</i> ; <i>A. palmata</i> ; <i>Diploria labyrinthiformis</i> ; <i>Porites porites</i> ; <i>P. astreoides</i> ; <i>Orbicella annularis</i> ; <i>O. faveolata</i> ; <i>Agaricia agaricites</i> | Reef restoration in one of the main pillars of the <i>Wave of Change</i> movement initiated in 2018 by the international hotel chain Iberostar. <i>Wave of Change</i> aims at contributing to the conservation of the oceans by engaging with the tourism sector. The main motivations of this project are experimental, biotic and idealistic. | 1) to determine current intraspecific diversity; 2) to enhance intra- and inter-specific diversity; 3) to maintain <i>in situ</i> and <i>ex situ</i> genetic bank; 4) to engage hotel clients and staff; 5) to characterise individual physiological traits of corals; 6) to enhance resilience in restored reefs | Despite the nursery still being developed, fragments of <i>A. cervicornis</i> , <i>P. porites</i> and <i>A. agaricites</i> have been maintained with 100% survival rate for three months to date.   | No information on the spatial extent of area intervened is available yet, because the transplantation strategy is currently being developed. As part of this strategy, the group aims to identify coral genotypes potentially less susceptible to environmental stress.                                       | The estimated budget spent from the beginning of the project in May 2018 to March 2019 is \$100,000 USD, including materials and construction of the land-based facility and salaries. In 2018 alone, \$40,000 USD were spent on construction (excluding salaries). The project is privately financed with annual funds destined to the <i>Wave of Change</i> initiative. From 2016 onwards, the group has taken over the responsibility of an <i>in situ</i> coral nursery that was set up and maintained in collaboration with FUNDEMAR. Research will be carried out by the scientific team of <i>Wave of Change</i> as well as by collaborating with international | best guess = 0.5; minimum = 0.2; maximum = 0.8 |

scientists who can use the facility to conduct their studies. The interspecific diversity of nursery-grown corals is being addressed through genetic analyses in collaboration with the University of California at Santa Barbara. Finally, the facility will be used as an outreach centre to teach and raise awareness about topics such as coral biology, the importance of reefs, threats to marine ecosystems, etc. to hotel clients and staff.

|   |   |   |   |   |  |  |  |   |
|---|---|---|---|---|--|--|--|---|
| <p>Dominican Republic, Punta Cana, Caribbean Sea, Fundación Grupo Puntacana (Program 1)</p> | <p>Nursery fragments are grown on A-Frames, tables and ropes at water depths between 3.5 and 5 m.</p> | <p><i>Acropora cervicornis</i>; <i>A. palmata</i>; <i>Orbicella</i> spp.; <i>Porites</i> spp.; <i>Pseudodiploria</i> spp.</p> | <p>The primary motivation of the project program is biotic and is focused on the enhancement of biodiversity and resilience. The secondary motivation is idealistic and concentrates on social reasons (e.g. development of alternative income opportunities for local communities and improved user experience for tourism, fisheries, ecosystem services etc.).</p> | <p>1) to prevent a potential local or regional disappearance of coral species through enhancement of successful sexual reproduction using fast growing, genetically diverse, nursery-reared fragments; 2) to reduce local environmental problems such as marine pollution, unsustainable wastewater treatment, uncontrolled fisheries and tourist carrying capacity; 3) to train local community members such as fishermen or dive centre staff in the installation and maintenance of coral nurseries and outplanting of nursery-grown corals; 4) to replicate the lessons learned in other parts of the Dominican Republic and other Caribbean island nations to improve coral reef restoration in Punta Cana; 5) to generate alternative income opportunities for members of the local community, especially for local fishermen</p> | <p>Nursery fragments are outplanted on the local, patchy, fringing reef using cable ties and galvanized nails at similar depths to fragments growing in the nursery.</p> | <p>Since 2014, a total of 8,810 <i>A. cervicornis</i> fragments (representing 5,394 linear meters of coral tissue) have been transplanted over almost 0.44 ha of degraded reef. Sexual reproduction has been consistently observed at both the nursery and surrounding outplanted sites.</p> | <p>The total estimated budget for 2018 was around \$93,000 USD resulting in \$211,363 USD ha<sup>-1</sup> yr<sup>-1</sup> when extrapolated from the actual area intervened (0.44 ha). This budget includes salaries, material, equipment, consumables, fixed-assets, infrastructure upkeep, and project-related expenses. For the next 3 years (2019 – 2021), if grant proposals submitted are approved, there is a plan to scale-up coral reef restoration efforts. These include an increase in the number of <i>A. cervicornis</i> fragments outplanted to approximately 5,000 fragments per year. FGPC estimates that over the next 3 years about 15,000 fragments can be transplanted over one ha of natural coral reef. The total estimated budget for the time interval 2019 – 2021 will be approximately \$950,000 USD, thus equalling the total cost of \$313,500 USD ha<sup>-1</sup> yr<sup>-1</sup>. The coral reef restoration programs are supported by the general budget of FGPC. Additional support is provided by private donations,</p> | <p>best guess = 0.8; minimum = 0.5; maximum = 0.9</p> |
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|  |   |  |   |  |  |   |   |  |
|--|---|--|---|--|--|---|---|--|
|  |   |  |   |  |  |   | national and international grants and institutions such as Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), The Nature Conservancy (TNC), Counterpart International (CPI), Caribbean Hotel and Tourism Association, Global Giving, and InterAmerican Development Bank (IDB) among others. |  |
| Dominican Republic, Punta Cana, Caribbean Sea, Fundación Grupo Puntacana (Program 2) | The donor colonies (fragments of opportunity) are cut by a diamond band saw into approximately one cm <sup>2</sup> pieces, which are then attached to cement discs made in-house and deposited into flow-through raceways. This program consists of three phases. The first phase identifies the best conditions for high survival and fast growth of the micro-fragments in the <i>ex situ</i> nursery and develops the protocols for the approach. The second phase identifies adequate restoration sites and develops outplanting protocols. During this phase, methods, tools and equipment are tested. The third phase will scale-up outplanting efforts with micro-fragments. | <i>Pseudodiploria strigosa</i> ; <i>P. clivosa</i> ; <i>Porites astreoides</i> ; <i>P. furcata</i> ; <i>Orbicella annularis</i> ; <i>Montastraea cavernosa</i> | The primary motivation of this project program is biotic (biodiversity enhancement), while the secondary is experimental (improve restoration approach, technology and methods). A tertiary motivation is idealistic (environmental education and outreach for the local community and tourists). | As above   | Micro-fragments will be outplanted using established protocols.  | By the end of the third phase, an estimate of 5,000 micro-fragments will be outplanted annually covering up to 200 m <sup>2</sup> per year. | The total budget for 2018 was around \$30,000 USD. The project duration is three years and the total estimated budget is \$850,000 USD (pending grant approvals). Funding bodies/partners are as above.   | best guess = 0.6; minimum = 0.4; maximum = 0.9 |
| Mexico, Chetumal, Caribbean Sea, Oceanus A.C.  | This project uses the coral gardening approach where corals are grown in <i>in situ</i> nurseries. Fragments of opportunity   | <i>Acropora palmata</i> , <i>A. cervicornis</i> ; <i>A. prolifera</i> ; <i>Porites</i> spp.; <i>Agaricia</i>   | The primary motivation of this program is pragmatic i.e., to recover reef ecosystem health and promote  | 1) to promote the rehabilitation of coral reefs through transplantation of 10,000 colonies every year at different sites in the Gulf of Mexico and the Mexican | The restoration sites are selected according to a set of established criteria. Every new site requires between three | The spatial extent of total area intervened for all restoration activities since 2014 is  | The total project budget was estimated to average \$150,000 USD per year since 2014 to outplant 10,000 colonies every year with an outplanting schedule   | best guess = 0.8; minimum = 0.5; maximum = 0.9 |

are rescued from donor areas and grown in the nurseries. Small concrete bases are attached to the reef and then corals from the nurseries are fixed to these structures (Fig. 2d). To increase the diversity at the restoration sites and promote natural resilience to climate change and local stressors, the program identifies the genetic material (genotypes) from healthy donor populations using the microsatellite technique. At least five genotypes are combined at each restoration site.

spp.; *Orbicella* spp.; *Diploria* spp.

recovery of environmental services of the reef as well as associated species populations and biomass with special emphasis on recovering protected and no-take areas. The secondary motivation is legislative, i.e., to restore coral reefs after environmental impacts such as ship-grounding or hurricanes depending on the location and site.

Caribbean; 2) to strengthen the resilience and adaptation potential of coral reefs by increasing diversity on restoration sites through the identification of genetic material from healthy donor populations that could be naturally resilient to climate change and local stressors; 3) to secure community and reef managers' engagement to build local restoration groups that work based on a self-sustainable strategy to multiply efforts, increasing benefits to local communities in the short and mid-term as well as helping the activities of the program to be maintained for a longer term

and five years of work until colonies of the first and second generation have grown to reproduce sexually. Every year, monitoring is carried out before and after transplantation at each of the sites to evaluate the survival and growth of restored corals. The overall average of transplant survival has been about 80%. At the oldest restoration sites initiated from 2013 onwards and maintained by the program, the outplanted coral fragments, which initially had average sizes of between 7 and 10 cm, have now (in 2019) grown to an average size of 30 cm in diameter. Some outplants have reached a diameter of up to 110 cm (Fig. 2e). About 30% of the transplants evaluated in 2019 at all sites had a size of 20 cm in diameter on average indicating that they have reached a reproductive size.

estimated as 6.3 ha to date.

of one coral colony per square meter. Therefore, the annual budget was estimated at \$150,000 USD ha<sup>-1</sup> yr<sup>-1</sup>. The restoration work of Oceanus A.C. is mainly artisanal and requires intensive maintenance to achieve results. Therefore, restoration efforts can only be sustained if the local community is involved to guarantee restoration success. The restoration program has initiated the formation of local restoration groups mainly consisting of members of the local fishing communities and other local organizations as well as the private sector (e.g., hotels) to support the restoration efforts. The program also seeks to engage local communities, service providers such as diving shops, hoteliers and managers to build local restoration groups and form a restoration network that helps increase restoration efforts along the Mesoamerican Reef. Establishing this network and applying different restoration strategies depending on the local stakeholder involved is envisioned to allow the program to become self-sustainable in the long term. The main partners of Oceanus A.C. for the development and scaling-up of the program have been the Comisión Nacional de Áreas Naturales Protegidas (CONANP), Summit Foundation, the Mesoamerican Reef Fund, Fairmont Mayakobá and OHL Group, with local partners such as Acuario de Veracruz, Fundación de Parques y Museos de Cozumel, hotels from Playa del Carmen

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| Mexico, Mexican Caribbean, Caribbean Sea, CORALIUM, Universidad Nacional Autónoma de México | <p>Since 2007, CORALIUM has been studying the basic biology of coral reproduction with the production of sexual recruits for restoration efforts beginning in 2011. Subsequently, it has focused on the development of low-cost techniques to scale-up the production of coral sexual recruits. This involves gamete collection in the wild, assisted fertilization and embryo husbandry in <i>ex situ</i> aquaria followed by outplanting of the sexual recruits to degraded reef sites. Restoration trials involve outplanting sexual recruits produced annually in the laboratory since 2011. From 2011 to 2014, the recruits were grown to juvenile size (up to 10 cm maximum diameter) in <i>ex situ</i> aquaria located in the Xcaret Ecopark. These colonies are now sexually mature as evidenced by the production of gametes in 2019. Since 2014, the research, in collaboration with SECORE International, has focused on scaling-up production and reducing costs by</p> | <p><i>Acropora palmata</i>;<br/><i>Orbicella faveolata</i>; <i>O. annularis</i>;<br/><i>Diploria labyrinthiformis</i>;<br/><i>Pseudodiploria strigosa</i></p> | <p>This project undertakes science-based research to promote and scale-up best practices for coral restoration using sexual recruits (experimental motivation) and to increase genetic diversity in restoration efforts in the face of global climate change (biotic motivation).</p> | <p>1) to reduce costs of techniques using larval propagation of corals 100-fold; 2) to conduct research to improve survivorship of sexual recruits 20-fold; 3) to scale-up coral restoration techniques to ecologically significant scales over a 10-year period</p> | <p>To reduce costs, coral larvae are settled onto the artificial substrates and outplanted two weeks post-settlement (one-polyp stage). The substrates are placed manually into natural gaps formed by the reef framework without using cement or resin. New substrate designs are in the process of being tested to increase recruit survival from 0.1% at one-year post-settlement currently to a target of 10% and to improve substrate retention in the reef framework.</p> | <p>CORALIUM, in collaboration with SECORE International and Experiencias XCARET Aquarium have outplanted coral sexual recruits with sizes ranging from one polyp to colonies with an estimated volume of 500 cm<sup>3</sup> on eight degraded reefs along the Mexican Caribbean from Cancun to Xcalak (<b>Table S7</b>, supplementary material). In total, the area of outplants corresponds to 0.15 hectares.</p> | <p>(Mayakobá chain) and from Mahahual and Xcalak, the Xcalak community, and tourist services providers from Cozumel, Puerto Morelos and Veracruz.</p> | <p>best guess = 0.7;<br/>minimum = 0.6;<br/>maximum = 0.9</p> |
|---|---|---|---|--|---|--|---|---|

outplanting sexual recruits at the one polyp stage settled onto tetrapod-shaped substrates, designed by SECORE International.

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| Puerto Rico, Culebra Island, Caribbean Sea, Sociedad Ambiente Marino | Coral nurseries were established in year 2003 and operated continuously for 15 years until the devastating impacts by hurricanes Irma and María in 2017. Following the hurricanes, tree coral nurseries were established at a depth of 9 m. Additional tree nurseries were established at a depth of 6-8 m, and at a depth of 7-12 m, to prevent further damage from coral bleaching and storm swells. Micro-fragmentation methods and direct coral cuttings have also been employed since the recent expansion. Direct transplantation has been conducted for emergency outplanting of fragments and/or detached colonies generated by vessel groundings, winter swells or hurricanes. | <i>A. cervicornis</i> ; <i>A. palmata</i> ; <i>A. prolifera</i> ; <i>Dendrogyra cylindrus</i> ; <i>O. annularis</i> ; <i>O. faveolata</i> ; <i>Madracis aurentenra</i> ; <i>Porites divaricata</i> ; <i>Eusmilia fastigiata</i> | The primary motivation of the project is biotic (i.e., to enhance biodiversity, coral reef connectivity and ecosystem resilience). The secondary motivation is experimental (i.e., testing alternative methods and designs, with aims to answer ecological research questions). The tertiary motivation is pragmatic (i.e., enhance the ecosystem services by improving shallow-water essential fish habitat, restoring depleted fisheries, restoring hurricane mechanical impacts, recovering shallow reef accretion following the 2005 post-bleaching mass coral mortality event; enhancing carbon sequestration, tourism, and coastal protection of local coral reefs). Also, an important local motivation is to restore coral reef ecological functions within areas formerly impacted by military training | 1) to expand the annual stock in the nurseries of <i>A. cervicornis</i> to 8,000 colonies, of <i>A. palmata</i> to 2,500 colonies, <i>D. cylindrus</i> to 500 colonies, and <i>O. annularis</i> to 500 colonies; 2) to restore approximately 3 ha of degraded reef per year till 2022; 3) to outplant a minimum of 20,000 colonies of four species grown in the nurseries by year 2022, including 13,300 colonies of <i>A. cervicornis</i> , 5,000 colonies of <i>A. palmata</i> , 1,200 colonies of <i>D. cylindrus</i> , and 500 colonies of <i>O. annularis</i> ; 4) to achieve a 25% increase in selected coral reef health indicators (i.e., live coral cover, fish biomass, and rugosity) at intervened sites for <i>A. cervicornis</i> and <i>A. palmata</i> ; 5) to design and implement an effective community-based plan for the rehabilitation of intervened reef areas, which encourages conservation and rehabilitation of ecosystem functions, and to contribute to the sustainability of the benefits of coral reefs; 6) to quantify the ecosystem services of intervened reef areas in current and future scenarios of intervention, variability and climate change | Overall, in the time span of 2003-2017 approximately 60,000 coral colonies (mostly <i>A. cervicornis</i> ) were harvested and outplanted to coral reefs in Culebra Island. Nursery-grown corals, fragments of multiple species, as well as micro-fragments and cuttings are directly outplanted to the reef using Portland marine cement mixed with lime to neutralize pH. Cable ties and masonry nails are also used in the case of <i>A. cervicornis</i> . An outplanting schedule with a density of one individual per square meter of reef for <i>A. cervicornis</i> and of one colony per four square meters for other species is often followed. | The project has intervened an area of ca. 6 ha, but many of these corals were lost during the 2017 hurricanes. The projected spatial extent of reef rehabilitation by year 2023 in total will be 8.4 ha, with a potential to increase the area intervened depending on funding and on community-based volunteer support. | The funds projected towards restoration for the period of 2019 to 2023 are \$1,327,206 (2018 USD), resulting in \$158,189 USD per restored ha per year or an estimated investment of \$50.26 USD per coral colony. These figures are based on the direct funds spent without accounting for in-kind contributions from the community. The real total estimated budget (including community-based in-kind support) for the period of 2019 to 2022 is \$2,311,280 (2018 USD) resulting in a total annual expenditure of \$275,480 (2018 USD) ha <sup>-1</sup> or a total estimated expense of \$87.53 per coral colony. Coral nurseries have been historically managed by SAM, and since 2011, in direct collaboration with the Centre for Applied Tropical Ecology and Conservation (CATEC) of the University of Puerto Rico – Río Piedras Campus, under a memorandum of agreement with the Puerto Rico Department of Natural and Environmental Resources (PRDNER), and NOAA Restoration Centers (NOAA-RC). The first 4-year sub-project of the post-hurricane long-term phase of the project will be financed through multiple sources, as described above. It will also involve extensive volunteer work, through a combination of | best guess = 0.7; minimum = 0.5; maximum = 0.9 |
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activities. Finally, the project is motivated by an idealistic rationale due to cultural reasons (i.e., community-based aim to restore formerly bombed grounds by the U.S. Navy which used local coral reefs in Culebra Island to support naval training activities between 1901 and 1975, rescue and stewardship of local coral reefs) and due to social reasons (i.e., fostering increased community involvement, job creation, nature education, environmental outreach, hands-on training in coral farming and reef rehabilitation methods). More recently, the project is being motivated by legislative reasons (i.e., restoration of *A. palmata* and *A. cervicornis* as part of mitigatory compensation project).

strategies involving students, fishermen, NGOs, and an internship program. SAM also plans to involve the hospitality sector. There will also be a large focus on a combination of outreach, educational and hands on strategies to prepare the next generation of coral farmers and coral reef restoration researchers in Puerto Rico.

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**Planned work**

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| Colombia, Gorgona National Natural Park, Eastern Tropical Pacific, ECOMARES | The project is presently gathering scientific information for future needs on coral restoration in the area. | <i>Pocillopora damicornis</i> ;<br><i>Pavona clavus</i> | The project is motivated by experimental reasons to improve restoration approaches for their use at Gorgona National Natural Park once restoration efforts are necessary. | 1) to determine the feasibility of coral nurseries in the area; 2) to determine the minimum coral fragment size of <i>P. damicornis</i> for successful survival and growth in coral nurseries; 3) to find the optimal fragment size for outplanting in terms of survival | The group's expertise in outplanting has been focused in the most abundant coral species in the area, <i>P. damicornis</i> . For this coral species, Portland cement mixed with sand | N/A | The cost for running the projects have been lower than expected because they are mostly experimental and have not carried out formal coral reef restoration activities yet. In 2018 the budget was \$10,000 USD. Partners: Universidad del Valle, Universidad | best guess = 0.7;<br>minimum = 0.5;<br>maximum = 0.9 |
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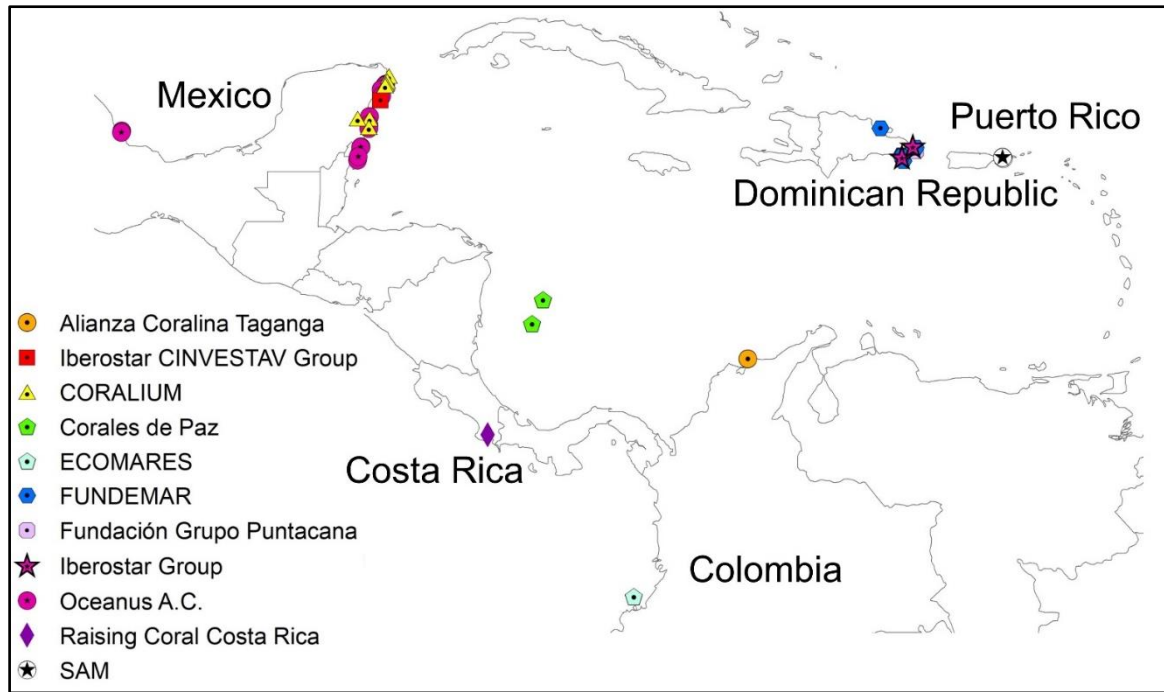
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|  |   |   |   | and coral growth; 4) to determine the effect of fish predation on <i>P. damicornis</i> during the outplanting; 5) to evaluate the use of enriched substrates for the massive coral species <i>P. clavus</i>   | and freshwater was used. So far, no information is available to determine the spatial extent (area) of restored habitat that will be obtained. |     | Javeriana de Cali, and Gorgona National Natural Park.  |     |
| Mexico, Cozumel National Natural Park, Caribbean Sea, The Iberostar & CINVESTAV Group: | The project aims to start with the development of four genotyped coral nurseries, two for <i>Acropora palmata</i> (3 and 5 m water depth) and two for <i>A. cervicornis</i> (10 and 13 m water depth). Each nursery will have 5 structures with a carrying capacity of approximately 40 fragments each enabling growth of 800 corals at a time. | <i>Acropora palmata</i> ; <i>A. cervicornis</i> ; <i>Pseudodiploria</i> spp.; <i>Siderastrea</i> spp.; <i>Diploria labyrinthiformis</i> ; <i>Orbicella</i> spp. | Coral reef restoration envisioned by both groups is mainly motivated by experimental, biotic (i.e., enhance biodiversity, ecosystem connectivity, and ecological resilience), idealistic and pragmatic reasons (i.e., enhanced water quality and ecosystem services, shallow-water essential fish habitat, restore depleted fisheries, enhanced tourism, and coastal protection of local coral reefs. | 1) to develop genotyped coral nurseries, which represent the coral diversity at Cozumel Island; 2) to establish sufficient material in the coral nurseries to develop activities for education, research, technological innovation, recreation and tourism; 3) to yield sufficient material for the establishment of transplant zones; 4) to collect gametes during the spawning season for larval rearing and use the larval propagation technique to grow sexual recruits at the transplantation site | N/A  | N/A | This is a collaboration between the Iberostar Group and CINVESTAV Group with the Cozumel National Natural Park and the Mexican Secretariat of Environment and Natural Resources (SEMARNAT). The program will engage with local communities, universities, government entities and tourism service providers to gather sustained funding into the future. The group is open to new partners interested in participating in the project. | N/A |

203 The primary motivations to carry out the coral reef restoration projects are biotic and experimental  
204 to equal parts (41.7%), followed by idealistic and pragmatic reasons (both 8.3%). Biotic (36.3%) and  
205 experimental (27.3%) reasons were important secondary motivations, followed by legislative reasons  
206 (18.2%), and pragmatic/idealistic motivations (both 9.1%). All except for one of the projects reported  
207 secondary motivations. The tertiary motivations reported by 5 of the 12 projects were mainly  
208 pragmatic (80.0%) and idealistic (20.0%).

209 Most projects have specific objectives to optimize/scale-up restoration approaches (51.1%), followed  
210 by providing alternative, sustainable livelihood opportunities (14.9%), and then in equal parts to  
211 promote coral reef conservation stewardship and re-establish a self-sustaining, functioning reef  
212 ecosystem (12.8%). The objectives to enhance ecosystem services for the future and the reduction of  
213 population decline and ecosystem degradation accounted for only 4.2% each of the specific project  
214 objectives.

215 The median total cost from all projects per year is \$93,000 USD ( $\pm$  \$32,731 SE) ranging between  
216 \$10,000 USD and \$331,802 USD. The median spatial extent of coral reef restoration intervention is 1.0  
217 ha ( $\pm$  1.3 ha SE) ranging between 0.06 ha and 8.39 ha. Project duration was as short as 1 year and  
218 could be as long as 17 years with the median project duration of 3 years ( $\pm$  1.5 years SE) to reach the  
219 project targets. Projects reported a median feasibility of 0.7 ( $\pm$  0.03 SE) ranging from 0.5 to 0.8 (**Table**  
220 **3**).



221

222 **Figure 1:** Map of coral reef restoration projects in Spanish-speaking Latin American countries and

223 territories.



224

225 **Figure 2:** Types of nurseries described in the text. a) Floating rope nurseries used in San Andrés and

226 Providencia islands for large-scale coral gardening (Photo: Corales de Paz); b) rope nurseries by

227 FUNDEMAR in Dominican Republic (Photo: Greg Asner); c) FUNDEMAR's floating *in situ* coral larvae

228 rearing tank (Photo: Paul Selvaggio); d) Oceanus A.C. diver outplants nursery grown corals in Veracruz,

229 Mexico (Photo: Oceanus A.C.); e) outplanted *Acropora palmata* coral in Puerto Morelos, Mexico  
230 (Photo: Oceanus A.C.); Raising Coral Costa Rica's tree nurseries in Costa Rica (Photo: David Garcia).

231

232 **Table 3:** Summary of total annual project costs, spatial extent of coral reef area intervened, project  
233 duration and feasibility from 12 case studies in the Spanish-speaking Caribbean and Eastern Tropical  
234 Pacific (Fundación Grupo Puntacana's restoration programs were treated as two independent  
235 projects). Error is given as standard error ( $\pm$  SE). Abbreviation: number of observations (N).

|        | <b>Total cost per year<br/>(2018 USD)</b> | <b>Spatial extent<br/>(ha)</b> | <b>Project duration<br/>(yrs)</b> | <b>Feasibility<br/>(best guess)</b> |
|--------|---|--------------------------------|-----------------------------------|-------------------------------------|
| Median | 93,000<br>( $\pm$ 32,731)                 | 1.00<br>( $\pm$ 1.30)          | 3.0<br>( $\pm$ 1.5)               | 0.7<br>( $\pm$ 0.03)                |
| Min    | 10,000                                    | 0.06                           | 1                                 | 0.5                                 |
| Max    | 331,802                                   | 8.39                           | 17                                | 0.8                                 |
| N      | 11  | 7                              | 12                                | 11                                  |

## 236 Discussion

237 Here we present the first comprehensive assessment of coral reef restoration projects in Spanish-  
238 speaking countries and territories of the Caribbean and Eastern Tropical Pacific (ETP), which are  
239 already being implemented or are in the initiation phase. These projects were identified through an  
240 open call for participation at the Reef Futures conference in December 2018, which aimed to bring  
241 together a large international community to develop and implement solutions to the global coral reef  
242 crisis.

243 We describe 12 coral reef restoration case studies in the Caribbean and Eastern Tropical Pacific that  
244 employ coral reef restoration techniques including direct transplanted, coral gardening, micro-  
245 fragmentation and larval propagation (Supplementary information, **Table S1**). With a median total  
246 project cost per year of \$93,000 USD, spatial extent of 1 ha, duration of 3 years and overall project  
247 feasibility of 0.7, we show that coral reef restoration projects in these countries are more cost-  
248 effective, have overcome the barriers of scaling-up restoration interventions, are persistent through

249 time, and have a higher likelihood of success than reported from previous literature [10, 12, 40]. For  
250 instance, the most recent published literature review on coral reef restoration presented a median  
251 value of \$400,000 (2010 USD) to restore 1 ha (10,000 m<sup>2</sup>) of coral reef, project duration of 1 year, an  
252 area intervened of 0.01 ha (108 m<sup>2</sup>), and survival of restored corals as an item-based success indicator  
253 of 0.61 [10].

254 The objectives for coral reef restoration are often undocumented in the published literature, thus  
255 extracting data on the objectives from published papers may lead to skewed results. For example,  
256 Hein et al. [39] reviewed 83 published coral reef restoration studies and observed that 60% of the  
257 studies reported on evaluating the biological response of the coral reef ecosystem to transplantation  
258 (outplanting) as a main project objective. The remaining 40% of studies included the following  
259 objectives: 1) to accelerate reef recovery post-disturbance (18%), 2) to re-establish a self-sustaining,  
260 functioning reef ecosystem (48%), 3) to mitigate coral loss prior to a known disturbance (18%), and 4)  
261 to reduce population declines and ecosystem degradation (15%). In comparison, we observed that  
262 when data are elicited directly from restoration practitioners, most coral reef restoration projects in  
263 the Caribbean and Eastern Tropical Pacific had the following objectives: 1) to optimize or scale-up  
264 restoration approaches (51.1%), followed by 2) to provide alternative, sustainable livelihood  
265 opportunities (14.9%). Similarly, the projects presented here were mostly motivated by biotic reasons  
266 such as to enhance biodiversity and experimental reasons (both 41.7%), followed by  
267 idealistic/pragmatic reasons (both 8.3%). In contrast, most motivations to restore coral reefs extracted  
268 from the published literature were dominated by experimental reasons, such as to improve the  
269 restoration approach and answer ecological research questions (65.3%) [10]. Many restoration  
270 projects presented here focused on harnessing social or economic benefits from coral reef restoration  
271 such as involving the community through inclusion in activities or educational programs to raise  
272 awareness or to provide alternative, sustainable livelihood opportunities for local communities. An  
273 assessment of social, economic, and cultural benefits derived from the restoration of coral reefs has  
274 been largely ignored by the published literature, which has mostly concentrated on outcomes related

275 to the ecology or described endeavours to improve restoration technology [10]. The present work is  
276 an attempt to bridge the gap between academics and practitioners. Academics tend to be more  
277 focused on small-experimental coral reef restoration attempts to answer questions of ecological  
278 concern, whereas practitioners are more focused on optimising and scaling-up restoration. Bridging  
279 the gap between academics and practitioners has been identified as critical for many fields of  
280 conservation [43, 44].

281 Coral reef restoration in the Caribbean and Eastern Tropical Pacific face challenges similar to those of  
282 restoration efforts elsewhere in the world. For instance, the Intergovernmental Panel on Climate  
283 Change (IPCC) concluded that, if no action is taken to reduce CO<sub>2</sub> emissions, coral reefs would decline  
284 by 70-90 % with global warming of 1.5°C above pre-industrial levels, whereas virtually all coral reefs  
285 (> 99 percent) would be lost with 2°C warming within the next 50 years [45]. Thus, while actions to  
286 reduce CO<sub>2</sub> emissions are drastically needed, restoration with heat resilient species is regarded as a  
287 key strategy to rehabilitate the ecological function and ecosystem services provided by coral reefs  
288 [35]. In addition to climate change, coral reef restoration in the Caribbean and ETP face other  
289 challenges such as overfishing, sedimentation, pollution, and non-sustainable coastal development  
290 [46-51]. The recent outbreak of Scleractinian Coral Tissue Loss Disease (SCTLD) has decimated coral  
291 populations and is of major concern to those attempting to restore corals in the Caribbean. Since its  
292 onset in 2017, SCTLD has caused widespread mortality of corals, especially in the Florida Reef Tract  
293 and the Gulf of Mexico [52, 53]. The vectors causing this disease or how it can be prevented are  
294 currently unknown but are most likely bacterial [52]. A further challenge to the restoration of coral  
295 reefs in the Caribbean and ETP is the apparent lack of funding and funding strategies. None of the  
296 countries have cohesive national plans for the restoration of coral reefs similar to the Reef Restoration  
297 and Adaptation Plan in Australia which has invested AUD \$100 million in 2018 to develop, trial, and  
298 deploy coral reef restoration interventions for the Great Barrier Reef (GBR) [54].

299 Despite the impediment of limited financial resources, considerable advances in coral reef restoration,  
300 both scaling-up of interventions and optimisation of techniques, have been achieved in Colombia,  
301 Costa Rica, Dominican Republic, Mexico and Puerto Rico. For instance, one of the largest and longest  
302 running projects (18 years) has plans to restore up to 8.4 ha, requiring outplanting 10,000 corals or up  
303 to 8,000 coral settlement bases with coral larvae per year. These interventions were led by pioneering  
304 environmental NGOs and foundations, who often procured un-paid volunteers to carry out much of  
305 the work. The interventions were also enabled by strong partnerships initiated by the champion  
306 organization with universities (e.g. Universidad Nacional Autónoma de México, University of Puerto  
307 Rico, Universidad del Valle, Universidad Javeriana de Cali, Universidad de Costa Rica), conservation  
308 management bodies and regulators (e.g. Natural Parks administrations, Departments of Natural and  
309 Environmental Resources and the United States National Oceanic and Atmospheric Administration),  
310 associations (e.g. Fishers Association, Caribbean Hotel and Tourism Association), national and  
311 international business partners (e.g. SECORE International), international environmental NGOs (e.g.  
312 Conservation International, The Nature Conservancy), tourist service providers (e.g. the Iberostar  
313 Group), private donations (e.g. Global Giving), international grant schemes (e.g. from Deutsche  
314 Gesellschaft für Internationale Zusammenarbeit, Counterpart International, InterAmerican  
315 Development Bank (IDB)) and in large part with local community groups. Coral reef restoration still  
316 remains an underfunded area in the Spanish-speaking countries and territories of the Caribbean and  
317 ETP despite the ecosystem services restored coral reefs could provide for the regions such as food,  
318 tourism income, protection against storms and wave surges [55, 56], and reduction in insurance  
319 premiums by offering coastal protection [57].

320 There are a few caveats that need to be considered when assessing the data within the present work.  
321 First, this review does not contain an exhaustive list of interventions in the Spanish-speaking countries  
322 and territories of the Caribbean and ETP. Additional projects exist or are planned, but were not aware  
323 of, or chose to not participate in our open call. Second, the projects presented here varied in their  
324 specific objectives, best practice protocols, and monitoring, which hindered their comparison. For



325 example, some projects were designed to improve and optimise the restoration approach  
326 (experimental projects), while others were more operational, i.e., aimed to scale-up the restoration  
327 of coral reefs by using already established restoration techniques. Furthermore, the projects used  
328 different best practice protocols or key indicators of restoration success, such as size of transplant and  
329 density of transplants which made a direct comparison between the projects difficult. Some projects  
330 lacked monitoring milestones to evaluate the survival, cover and health conditions of outplanted  
331 corals beyond year one. Yet, post-restoration monitoring is an imperative method needed to confirm  
332 that outplanted corals are self-sustaining which, from an evolutionary perspective, is the ultimate goal  
333 of any restoration effort [3-5]. Third, evaluation of the overall project feasibility or the likelihood of  
334 success to reach specific project objectives is naturally linked to local conditions and circumstances,  
335 thus may be a subjective measure directly related to the experience of the practitioner. More  
336 quantitative measures of overall project feasibility (e.g., based on measurements) would be a  
337 considerable improvement over the qualitative (derived from expert elicitation) approach.

338 Prior to any conservation action, a prioritisation of interventions based on decision-support  
339 frameworks is recommended to help practitioners increase their planning rigor, project accountability,  
340 stakeholder participation, transparency in decisions, and learning [58]. Cost-effectiveness analysis is  
341 such a tool that allows for the evaluation and prioritisation of conservation interventions [59]. This  
342 analysis relates the costs of a project to its key outcomes or benefits i.e., the specific measures of  
343 project effectiveness [59, 60]. Although this work includes all data required for a cost-effectiveness  
344 analysis (see Supplementary material), we considered that comparing the different projects against  
345 each other will be inappropriate given the variety of their project objectives (e.g. experimental vs.  
346 operational) and the lack of standardisation in reporting on cost, feasibility and key outcomes.

347 Future collaborations between academics, local communities and practitioners will be crucial if we  
348 want to achieve restoration at meaningful ecological, spatial and social scales [61]. Unfortunately, the  
349 language barrier often inhibits such collaborations. For instance, Amano et al. [62] argues that

350 languages are still a major barrier to global science by showing that more than 35% of the knowledge  
351 in conservation is missed by those who only look at peer-reviewed literature in English. Many  
352 practitioners who carry out large-scale coral restoration projects only convey their knowledge in the  
353 form of unpublished reports and grey literature [10], which adds another level of complexity to the  
354 loss of information on restoration efforts. Here we close this gap by accessing this knowledge and  
355 overcoming the language barrier.

356

## 357 **Conclusions**

358 Although not previously highlighted by the published literature, there are many coral reef restoration  
359 projects currently in progress in the Spanish-speaking countries and territories of the Caribbean and  
360 Eastern Tropical Pacific. Most of these projects are being carried out by pioneering civil organizations  
361 often in strong partnerships with universities, conservation management bodies and regulators,  
362 tourism operators, the private sector, associations, and local community groups. While coral reef  
363 restoration has been portrayed as too expensive and challenging with regards to spatial scale,  
364 duration, and success, the projects presented here have shown that many of these barriers have  
365 already been overcome. These pioneering endeavours were often possible by in-kind commitments  
366 of staff and volunteers as well as involvement of the local community and tourism operators, thus  
367 socio-economic aspects play a substantial role in coral reef restoration in the Caribbean and Eastern  
368 Tropical Pacific. Strong national plans for restoration in conjunction with national and international  
369 funding are needed to multiply the already existing activities made by Latin-American organisations  
370 to improve the health and status of coral reefs in the Caribbean and Eastern Tropical Pacific. From this  
371 compilation of data and knowledge, it is apparent that it would be beneficial for coral reef restoration  
372 practitioners in this area to coordinate their efforts with each other and make sure they are sharing  
373 and implementing their best practices protocols to standardise efforts and track restoration progress  
374 by specific, measurable, achievable and repeatable metrics of success through time.

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381

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