16

REEF RESTORATION IN THE EASTERN TROPICAL PACIFIC, A CASE STUDY IN GOLFO DULCE, COSTA RICA

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ABSTRACT

Coral reef restoration is a fast-growing area of research in many parts of the world. However, coral propagation and reef restoration in the eastern tropical Pacific (ETP) have been very limited (Guzmán 1991; Liñan-Cabello et al. 2010; Tortolero-Langarica et al. 2014; Nava and Figueroa-Camacho 2017; Lizcano-Sandova et al. 2018; Tortolero-Langarica et al. 2019). Compared to other reefs worldwide, the ETP is a region with low coral biodiversity and less-developed reef frameworks (López-Pérez 2017). However, the coral reefs here persist in an environment characterized by wide fluctuations in temperature, pH, and salinity. Reefs in the Golfo Dulce of Costa Rica appear to be particularly resilient. During the 2016 warming event, almost all corals in Golfo Dulce were severely bleached for three to four months, but most survived. It is unclear whether the reasons for this are biological (corals conditioned to withstand extremes, high food availability) or physical (nutrients, mixing). For whatever reason, the resilience of these corals is a sound reason for developing techniques for their propagation and outplanting. We describe here the results from the first three years of coral propagation in an underwater nursery in Golfo Dulce and pilot outplanting at several sites on Golfo Dulce reefs. We also provide a summary of what was learned about reef propagation and restoration techniques for the major ETP corals, as well as some unanticipated challenges of reef restoration in general.

INTRODUCTION

Eastern Tropical Pacific

Coral reef ecosystems of the ETP extend from the Gulf of California to Ecuador, including the oceanic islands of Revillagigedo, Clipperton, Cocos, Malpelo, and Galápagos. The recent and comprehensive book *Coral Reefs of the Eastern Tropical Pacific* edited by Peter Glynn, Derek

Manzello, and Ian Enochs (2017a) provides extensive background on these reefs, and we summarize some of the Glynn et al. (2017b) points here, particularly those that are relevant to current-day restoration efforts.

Oceanographic conditions along the ETP coast are driven by local winds (including strong seasonal gap winds), eddies, and interaction with the eastern boundary currents. Surface waters are typically warm and have relatively low salinity and pH (Fiedler and Lavín 2017; Glynn et al. 2017b). Regions of seasonal upwelling can bring much cooler, low pH waters to the surface, such that many corals along the ETP are exposed to highly variable conditions and high rates of bioerosion (Alvarado et al. 2017). The ETP is strongly affected by the El Niño Southern Oscillation (ENSO), and warm ENSO events have caused widespread mortality of ETP corals in the years 1982–1983 and 1997–1998, which caused massive coral bleaching and mortality (Cortés et al. 1984; Glynn 1984; Jiménez 2001), and most recently in 2016 (Alvarado et al. 2020).

ETP reefs are isolated from most other Pacific reef regions by the Eastern Pacific Barrier, a vast expanse of ocean separating the Central and Eastern Pacific, across which few dispersing larvae can survive. Only 47 species of scleractinian corals have been identified in the ETP (Cortés et al. 2017), compared to about 72 species in Hawaii, and more than 600 in the Coral Triangle (Veron et al. 2015). The main coral genera of the ETP are *Pocillopora*, *Porites*, *Pavona*, and *Gardineroseris* (Glynn et al. 2017b).

The isolation has resulted in a shift in life-history strategies of ETP coral species from those of their western Pacific counterparts, favoring autotrophic larvae that can travel long distances (Baird et al. 2009). In the western Pacific, *Pocillopora damicornis* is usually a monthly brooder, but in the ETP it appears to be a monthly broadcaster. Similarly, while species within the genera *Porites* and *Pavona* normally spawn annually, in the ETP they appear to spawn over several months (Glynn et al. 2017c). This shift in spawning strategies likely reflects natural selection within a patchy geographic distribution of reefs and an environment with frequent disturbances (Glynn et al. 2017c).

Regardless of the rather harsh environment and low coral diversity of ETP reefs, there are many reasons to study their capacity for reef restoration. First, these reefs and coral communities support high-marine biodiversity (Cortés 1997; Cortés et al. 2017) and thus are essential in the life support of the tropical marine ecosystems here. Second, the corals appear to be resilient; they have demonstrated an ability to survive months of severe bleaching and an ability to recover (in terms of coral cover) following bleaching events, despite the low rates of coral recruitment (Glynn et al. 2017c). Third, the relative ecological simplicity of these systems, at least in terms of coral diversity, allows one to more easily understand the response of the system to restoration.

In addition, for the Costa Rican Pacific, the additive impacts of pollution, invasive species, etc., are relatively low. In Costa Rica, marine conservation is gaining attention similar to that applied to their terrestrial environments; e.g., the recent decree by the Costa Rican government to protect Costa Rican coral reefs—"Promotion of restoration and conservation initiatives for the recovery of coral ecosystems" (Excecutive decree N°41774-MINAE, June 6, 2019). This case study describes findings from the first three years of a coral propagation and outplanting project in Golfo Dulce, a small embayment of the Costa Rican Pacific (Cortés 2016).

Study Site

The Golfo Dulce is a deep basin with a shallow sill at the entrance and is rimmed by a shallow, narrow shelf (Hebbeln and Cortés 2001; Cortés 2016) that supports several coral reefs and coral communities (Figure 16.1). The main impacts on these reefs are sedimentation from land and

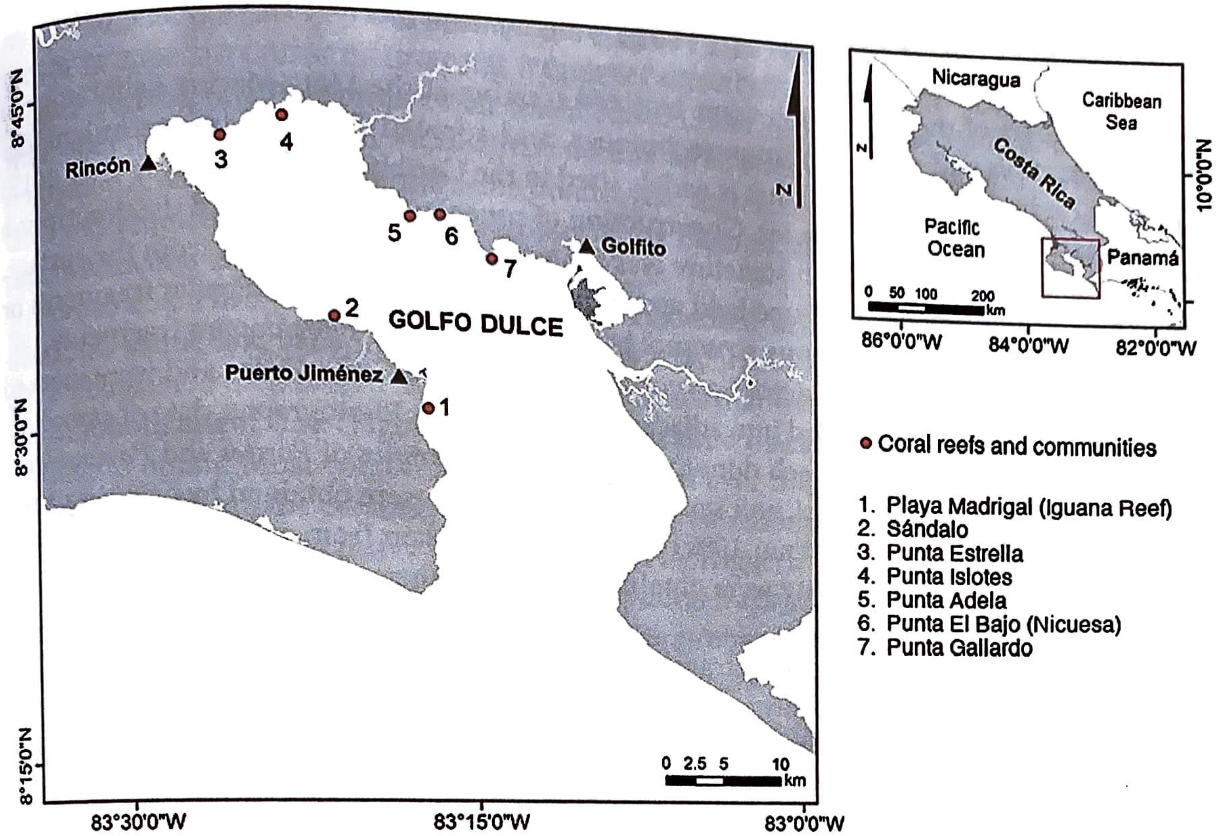

Figure 16.1 Coral reefs and coral communities in Golfo Dulce, South Pacific coast of Costa Rica. This figure is modified from Cortés (1990). Numbered locations show areas with coral reefs and coral communities. The underwater nursery is located near Punta El Bajo (Nicuesa).

warm water events. While the threat of sedimentation has decreased due to improved land-use practices, the threat of climate change continues to increase. In fact, the start of the restoration effort was delayed for many months because of severe bleaching of Golfo Dulce corals between February and May of 2016. Several potential outplanting locations were identified based on previous studies by Jorge Cortés and Juan José Alvarado, whose combined body of work on Golfo Dulce corals and reefs document their historical development as well as recent cycles of degradation/recovery (Cortés and Murillo 1985; Cortés 1990; Cortés 1991; Cortés 1992; Cortés et al. 2010; Alvarado et al. 2015).

In September 2016 a pilot coral restoration project was installed in Golfo Dulce, Costa Rica (Villalobos-Cubero 2019). The goal of the project was to evaluate propagation and outplanting techniques of fragments obtained from the most common species: *Porites lobata* and *P. evermanni*; *Pavona gigantea* and *P. frondifera*; and *Pocillopora* spp. (tentatively identified as *P. damicornis* and *P. edouxi*). Specimens of *Psammocora* spp. were also propagated on an experimental basis, but were not a target for restoration. The propagation was restricted to an in situ nursery located near 8°39.3′N, 83°16.3′W. The underwater nursery initially consisted of four tree structures in which fragments were closely monitored for growth in relation to orientation, initial fragment size, position (depth) within the tree, and temperature. During the third year the nursery was expanded to include four additional tree structures and two rope structures.

TECHNIQUES AND METHODS

Several members of the restoration team received training at the Mote Marine Laboratory in coral propagation and reef restoration techniques, and adapted the coral tree technique described by Nedimyer et al. (2011) that is widely used in the Caribbean (Schopmeyer et al. 2017) for propagation of ETP coral species. Construction of rope structures followed the description in Frias-Torres et al. (2018). Each structure was placed approximately 3–5 m from the surface, in waters 8–12 m deep. A single tree held approximately 150 *Pavona* and *Porites* fragments or 72 *Pocillopora* fragments. Each rope structure had a capacity of 200 *Pocillopora* fragments.

Coral donors were identified across several different reefs in Golfo Dulce and were marked with a numbered plastic tag nailed into adjacent hard substrate. Photographs, date of sampling, depth, and GPS coordinates of each donor were recorded. Samples of *Porites* and *Pavona* were obtained with hammer and chisel, and samples of *Pocillopora* were obtained by breaking a few branches from the colony. Less than 10% of a colony was taken from each donor, and when possible, fragments of opportunity were obtained, assuming they were derived from the nearest colony.

Pocillopora samples were further fragmented to approximately 2–4 cm long branches, and each labeled fragment was suspended in the tree structure with monofilament (Figure 16.2(a)). A few fragments were first glued onto ceramic discs, which were then suspended with

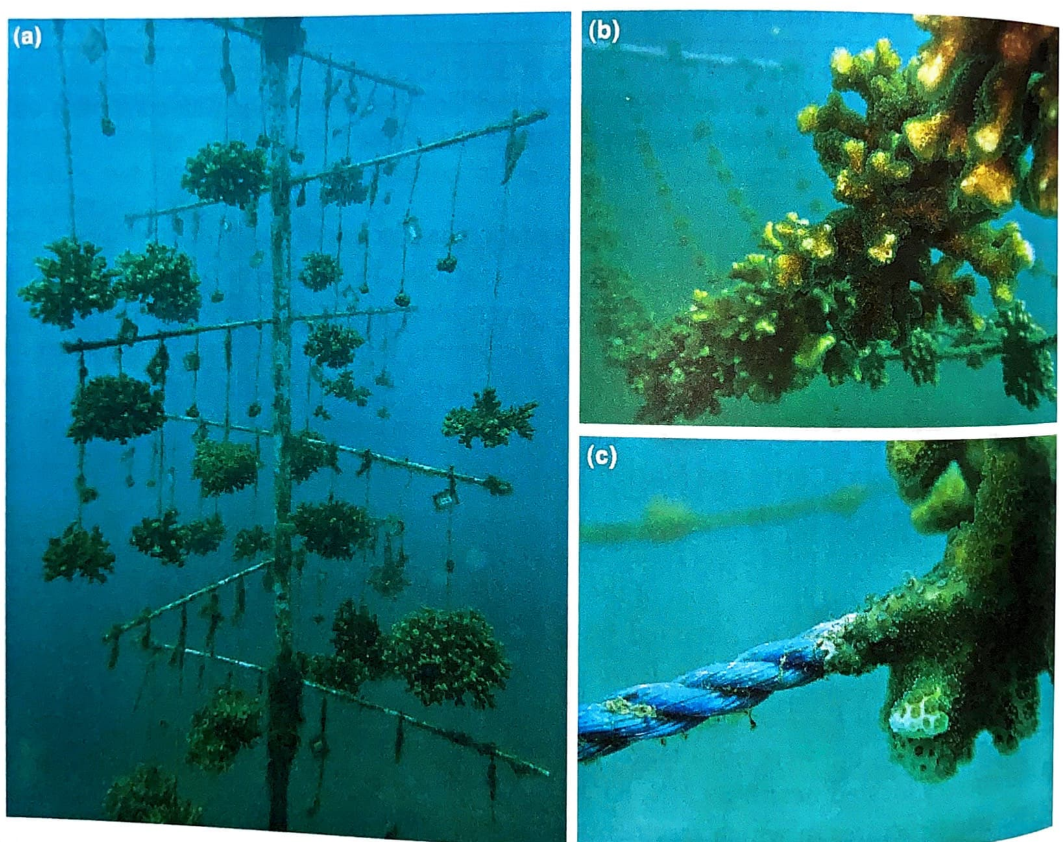

Figure 16.2 (a) Tree structure for growing branching corals; (b) rope structure for growing branching corals; and (c) growth of *Pocillopora* fragment over polypropylene line.

monofilament, but this step was deemed unnecessary after a few months. *Pocillopora* were also grown in rope structures by inserting fragments directly between the twines of twisted rope (Figure 16.2(b), (c)). The project first tested natural fiber rope, such as hemp and manila (⅜" wide), but these disintegrated within three months, so all lines were replaced with nylon or polypropylene rope. Fragments of the same donor were segregated by rope, so that a single donor label was required for each rope. Regardless of the method, all fragments overgrew the line or rope within one to two months.

Porites and *Pavona* samples were micro-fragmented using a Gryphon Aquasaw with a diamond blade, and each micro-fragment was attached to a ceramic disk with thick super glue. These were then placed in small egg-crate trays that were suspended in the tree nursery with monofilament line (Figure 16.3(a)). All ceramic disks were labeled and recorded according to donor. Most coral fragments had grown over the exposed skeleton of the micro-fragments and onto the ceramic disc within one to two months. Early deployments of *Porites* and *Pavona* experienced heavy mortality caused by triggerfish bites (*Balistes polylepis*). Plastic mesh grid (1×1 cm squares) was placed over coral trays to eliminate fish predation (Figure 16.3(b)). While these grids resolved the fish bite problem and increased survivorship, they also became overgrown with algae and other fouling organisms, requiring frequent cleaning (Figure 16.3(c)).

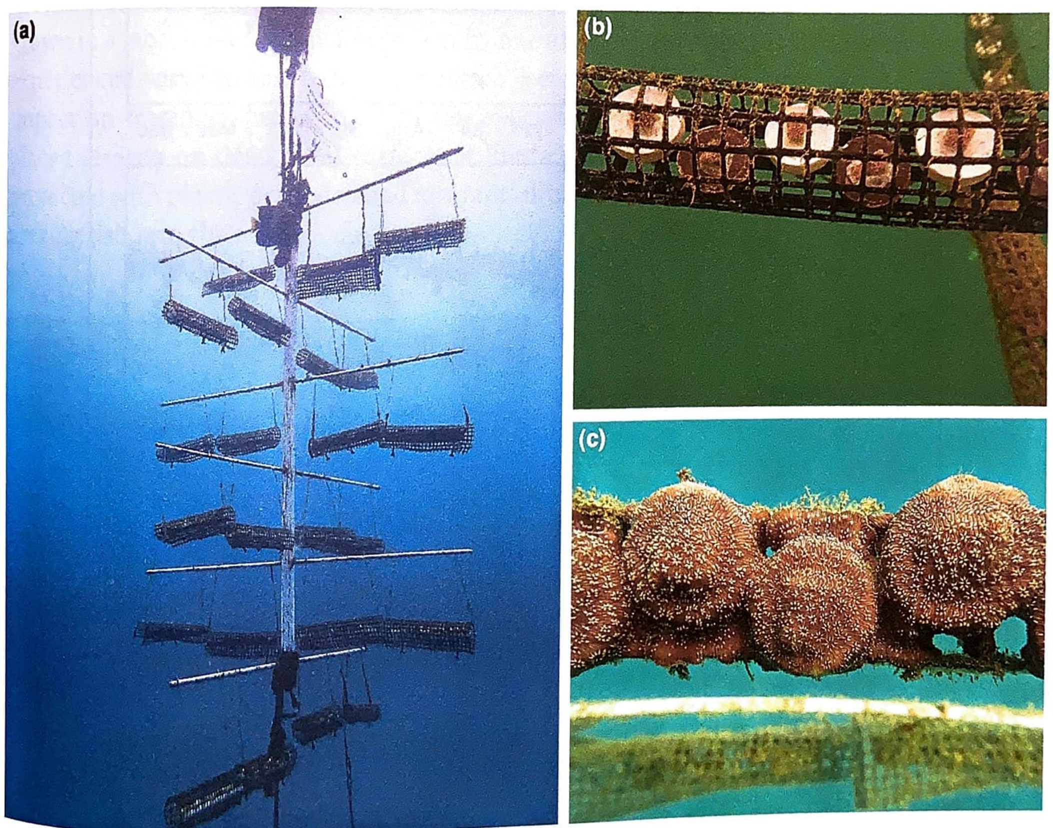

Figure 16.3 (a) Tree structure for growing massive corals; (b) egg-crate tray with ceramic disks holding *Porites* fragments and protected with plastic grid; and (c) growth of *Pavona* fragments after 10 months.

MONITORING

Several nursery structures were fitted with HOBO® Water Temp Pro v2 data loggers that were set to record the temperature every 10 or 15 minutes. The same type of sensor was also placed at each outplant site. The data documented similar temperature fluctuations across all sites, although deeper sites were slightly cooler than shallower sites. Of note in this region are periods of strong temperature fluctuations that coincide with the tidal cycle (Figure 16.4); these events appear to reflect cool water intrusions at a depth that contributes to the formation of a shallow thermocline. Because the sensors remain at a fixed level that is relative to the bottom, the vertical rise and fall of the thermocline are reflected in the temperature record. During periods with a strong thermocline, the nursery corals experience twice-daily temperature fluctuations of up to 9°C.

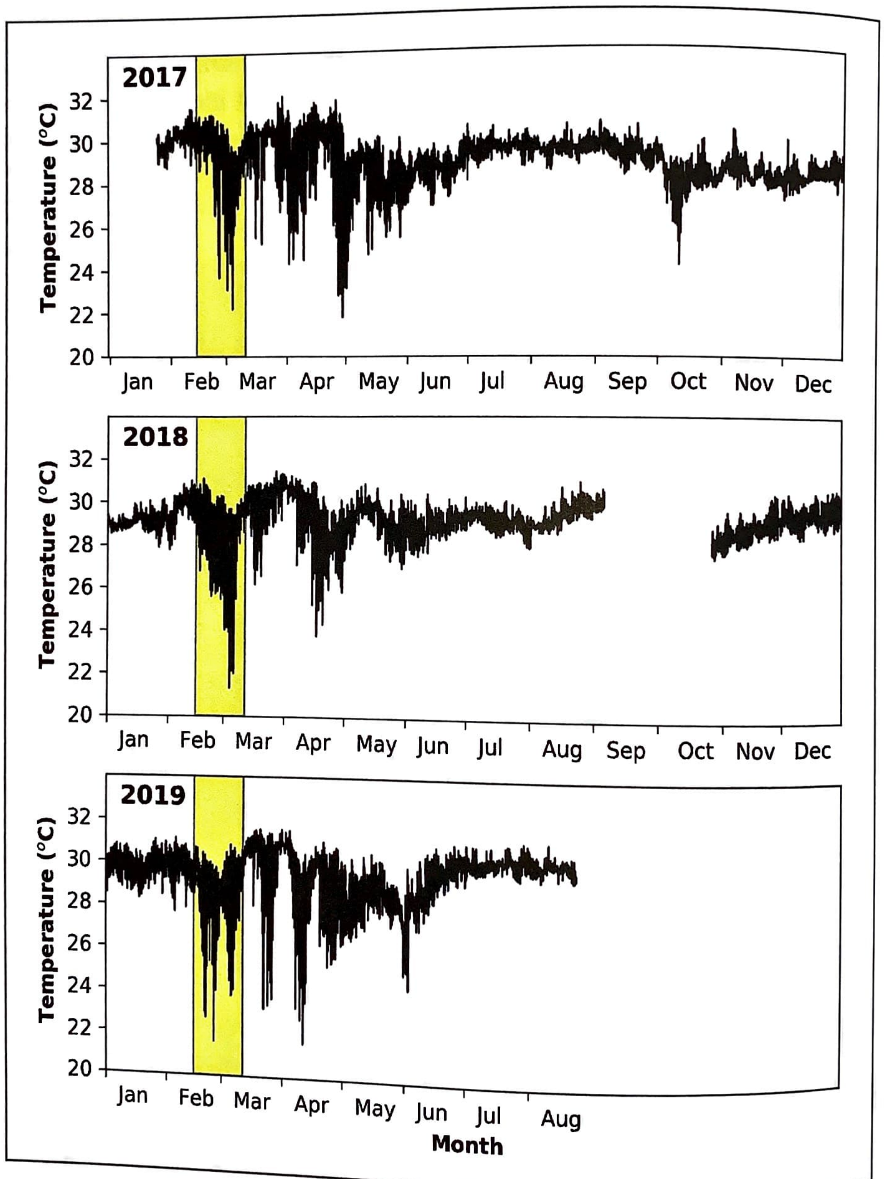

Figure 16.4 Monthly temperatures (°C) at the Golfo Dulce coral nursery, February 2017 through August 2019 (from HOBO® temperature sensors placed on the top branch of Tree 2 in the nursery).

Fragment growth was monitored with a combination of monthly photographs and Vernier caliper measurements. Photographs of each disk were analyzed using ImageJ software (Schneider et al. 2012), in which the area of the fragment was calibrated to the known area of the disk (Figure 16.5(a)). Branching coral growth was more problematic, and several techniques were tested, including wet weight, volume displacement, photography against a scaled background, and direct measurement of coral height and width. Monthly photographs of *Pocillopora* fragments provided the valuable information regarding both coral size and health, but they were not as quantifiable as taking three-dimensional measurements (Figure 16.5(b)). The three-dimensional measurements were converted to *coral volume* following the technique described by Salinas-Akhmadeeva (2018), and was considered representative of the *ecological space* occupied by the coral.

Growth and mortality of fragments in the nursery varied greatly with species. *Pocillopora* fragments had very low mortality, and grew to outplantable size within 8–12 months. *Pavona* fragments also had very low mortality (5%), and within 6–10 months, often grew rapidly over and beyond the ceramic disks, including over fouling organisms such as barnacles and serpulid worms. In contrast, fragments of the most common species in Golfo Dulce, *Porites* spp., had high mortality rates (average 70%), even when grids were used to eliminate *B. polylepis* bites. The high mortality was suspected to be a problem associated with the very small polyps of *Porites*, which decreased their ability to compete with rapidly growing fouling organisms. This species was also commonly used by invertebrates as a substrate for laying their eggs. *Porites* spp. grown in a land-based aquarium facility by one of us (Marín Moraga) with highly filtered water experienced very low mortality rates, which is evidence that fouling organisms have a negative impact on fragment propagation in this species. *Porites* fragments of opportunity that were placed directly on dead coral surfaces at Punta Adela reef in Golfo Dulce, particularly those protected with plastic grid, also had low mortality rates, perhaps because the grid allowed small grazing fish into the mesh enclosures.

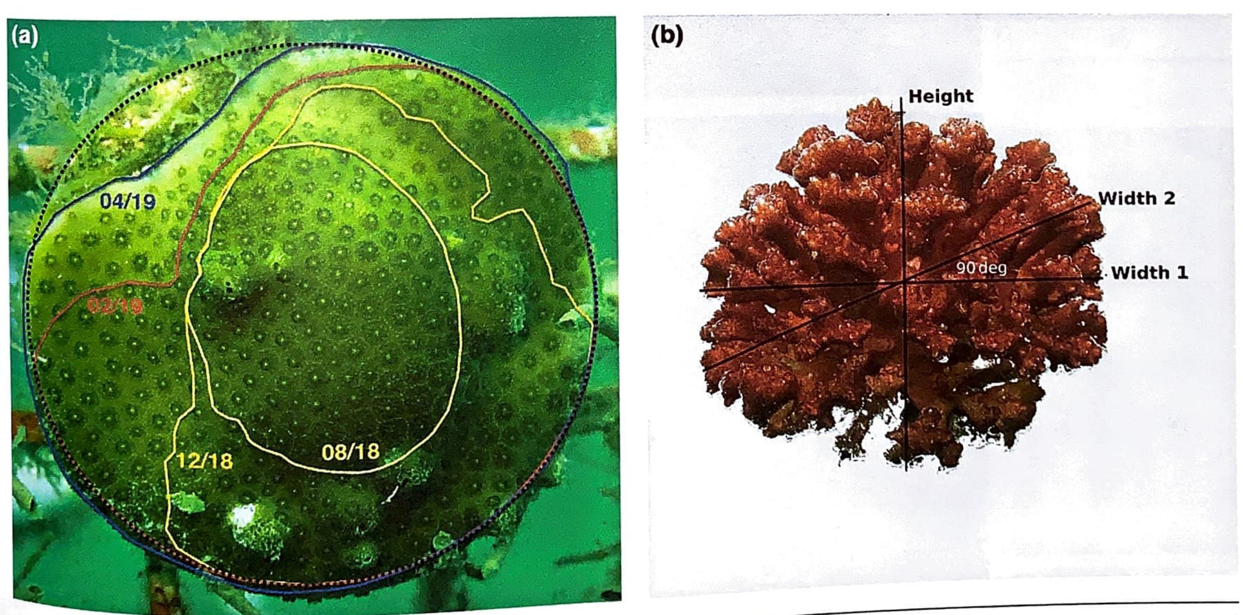

Figure 16.5 (a) Example of area determination over time using ImageJ software. Solid colored lines correspond to growth edge of fragment for a particular month/year; black dashed line shows outline of ceramic disk. (b) Three-dimensional measurements of the branching coral *Pocillopora* sp.

Test outplantings began once the corals had grown to a sufficient size—about 6–8 months for *Pavona* and *Porites* and about 8–12 months for *Pocillopora*. Test outplantings were first performed on the same reefs as the original donors, then monitored for a year or more to evaluate the outplanting method as well as the health and growth of the outplants. *Pavona* and *Porites* fragments were outplanted by inserting the stem of the ceramic disk into a hole that had been drilled into the substrate (following the protocol of the Mote Marine Laboratory); underwater epoxy (AquaMend®) was used to hold the fragment in place if the stem did not fit snugly into the hole. The coral fragments were typically outplanted in clusters of 10 or more from the same donor to evaluate the fusion process between the fragments (Figure 16.6). Occasionally, fragments were planted randomly and alongside small fragments of opportunity that were epoxied directly to a bare coral substrate on the reef.

Pocillopora fragments were initially outplanted using the *nail-and-zip-tie* technique; underwater epoxy was occasionally used to stabilize unstable colonies. For *Pocillopora* grown in rope nurseries, the entire rope was transported to the outplant site and tacked to the substrate using

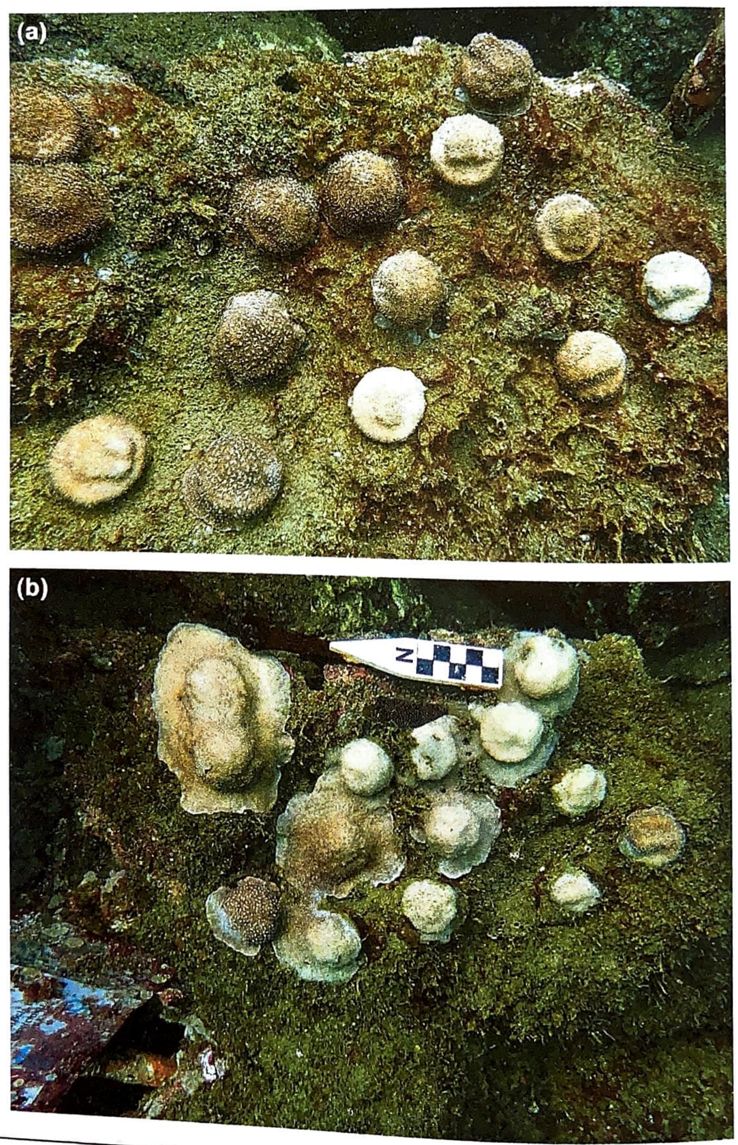

Figure 16.6 (a) *Pavona gigantea* outplants at Punta Gallardo, June 27, 2017; (b) The same *P. gigantea* outplants on July 28, 2018.

fence staples to secure the rope to the substrate (i.e., U-shaped, double-pointed nails). Test outplantings were performed at five locations: Punta Gallardo, Punta Adela, Punta Islotes, Punta Bejuco, and Sándalo Reef. Between three and 10 colonies were outplanted in small clusters with spacing of 10 cm to 1 m. Recent outplantings with higher numbers of corals have focused on the Punta Islotes and Punta Bejuco reefs. Initial survival rates of *Pavona* outplants were low (~53%) (Villalobos-Cubero 2019) and reflect almost total mortality of outplants on crystalline versus carbonate rock surfaces at Punta Gallardo; mortality rates decreased with later outplants on old reef substrate at Punta Islotes and Punta Bejuco (Table 16.1). Most *Pavona* outplants extended their growth over the substrate within a few months, and many were fused with neighboring colonies within one year. The initial *Porites* outplants had a low survival rate (41–64%; Table 16.1), which appeared to be due to *algal gardening* by damselfish that smothered the outplants. Placing grids over the coral outplants for 6–12 months greatly reduced this mortality (Figure 16.7(a)). *Porites* outplants also fused if they were from the same donor, but outplants from different donors were obvious by a distinct line of competition between abutting colonies (Figure 16.7(b)). Survival rates of *Pocillopora* outplants improved from 65% to more than 90%, probably because of better outplanting techniques that prevented colonies from becoming dislodged from the surface. *Pocillopora* grew rapidly over the zip ties but often required several months to grow solidly over the substrate and appeared to fuse with the substrate more rapidly when epoxy was used (Figure 16.8(a), (b)). Outplanting rope segments with multiple coral colonies (Figure 16.8(c)) proved to be a more efficient outplanting

Table 16.1 Percentage of outplant survival for the first three years of the Golfo Dulce Project. Outplant sites are listed from left to right in order of dates of the first outplantings. Note: Punta Bejuco is located about halfway between Punta Estrella and Islotes

Species	Punta Gallardo	Punta Adela	Islotes	Punta Bejuco
Porites spp.		64	41	100
Pavona gigantea	53		67	100
Pocillopora spp.	65		100	95

Figure 16.7 (a) Caged *Porites* spp. outplants at Punta Adela reef, June 30, 2017. (b) some of the same *Porites* spp. fragments, October 15, 2019 (the cage was removed in January 2018). Note the boundary between two lower colonies where fragments from different donors were outplanted adjacent to each other.

Figure 16.8 (a) *Pocillopora* colony (P4) outplanted on May 5, 2018, using nail and zip tie, and showing two fragments from the colony epoxied to substrate. (b) P4 on October 15, 2018. (c) *Pocillopora* colonies (Donor 12) from the rope structures outplanted on December 11, 2019, by stapling the rope to the substrate and stabilizing colonies with epoxy when necessary.

method, but this recently employed technique will require further evaluation regarding the impact on survival rates of the colonies. The shallowest *Pocillopora* outplants on the old reef flat of Punta Bejuco (1.6–2 m depth) experienced more paling, bleaching, and mortality than *Pocillopora* outplanted in waters 3–8 m depth.

Based on genetic analyses of 21 samples from *Porites* colonies on a shallow local reef (Punta Adela) and five fragments in the coral nursery, the *Porites* colonies in Golfo Dulce are predominantly *P. evermanni*. The Punta Adela sampling followed the methodology for a previous study at a nearby reef in Golfo Dulce (Boulay et al. 2014), which showed a 1:2 ratio of *P. lobata* to *P. evermanni*. In contrast, only one of the colonies from the shallower Punta Adela reef, and none of the nursery corals, was *P. lobata*. Sampled colonies of *P. evermanni* displayed good genotypic diversity, however, with 18 genotypes represented among the samples.

COMMUNITY INVOLVEMENT, VOLUNTEERS, AND CITIZEN SCIENCE

Educating and engaging local communities about coral reef restoration was a priority from the beginning of the operation. Research to understand how persons from local communities use and perceive Golfo Dulce reefs was begun several months before the establishment of the coral nursery (Villalobos-Cubero 2019). The results revealed strong differences in perception about coral reefs between fishermen, people working in tourism, and non-reef users. Interviewees confirmed a high frequency in visitation to coral reefs and communities in the gulf, mainly for snorkeling. Their perceptions were that sedimentation and agrochemical pollution were the main factors affecting corals in the area. About two-thirds of the interviewees considered the lack of information as a strong obstacle for conservation and management initiatives, and the project's work within these local communities has proceeded to close that gap through scientific and public talks, presentations in schools, and participation in coastal clean-up events. All interviewees acknowledged the value of coral reefs and the need to protect them, but they did not support the formation of new marine protected areas or restrictions to the use of these ecosystems. The project also collaborated with a local non-governmental organization (NGO) and an ecolodge to train six persons from nearby communities in open-water diving and safe coral gardening and monitoring; these trainees participate regularly in restoration activities, as permitted by space on the boat.

The project has received hundreds of unsolicited requests to volunteer or intern, and many such requests are from local communities. The project is dedicated to creating ways to include stronger participation with volunteers and interns; however, the remoteness of the Golfo Dulce, the lack of local diver support, and the cost of boat rentals have so far postponed the implementation of a safe and affordable volunteer/intern program. The project has also formed the basis for several undergraduate and graduate research projects to evaluate propagation and outplanting techniques—and to follow changes in community structure, immunological responses in corals, and techniques for tracking coral growth.

DISCUSSION

The Golfo Dulce restoration project is the first large-scale evaluation of an underwater coral nursery as a tool to accelerate coral propagation and restoration in the ETP. It was founded with a vision to restore reefs in a scientifically supported way and to serve as an example for other coral restoration projects in the ETP. The project is guided by the four principles of successful restoration outlined in Suding et al. (2015) and aims to (1) be informed by historical data and future forecasts, (2) ensure ecological integrity, (3) engage and benefit local communities, and (4) be sustainable over the long term. The project is still evaluating the long-term stability of restoration, e.g., tracking recruitment of corals and other marine organisms at restoration sites, but overall, the project has been successful. A total of 1,500 colonies of seven coral species were propagated in the Golfo Dulce nursery, and about 300 were outplanted and are being monitored. The current standing stock of propagated corals in the nursery is maintained at 1,000–1,200 corals. While the overall numbers are small, the project has tested multiple techniques in both propagation and outplanting, and has set a baseline for continued research and scaling up while adhering to the principles of successful restoration.

We found that all coral species except *Porites* were easy to propagate and outplant. *Pavona* species grew well on ceramic disks, and *Pocillopora* grew equally well in tree and line structures. The choice of structure is a balance between efficiency (line nurseries are most efficient) and research (ease of moving coral fragments for experiments).

One of the biggest successes of the project so far is the ability to propagate more than a thousand colonies of *Pocillopora*, a species that had become difficult to find in the natural environment of the gulf. Our goal with this species is to re-establish a self-sustaining and genetically diverse population in Golfo Dulce.

CONCLUSION

Adhering to the Suding et al. (2015) principles has required a slower approach than many other projects—and less emphasis on scaling up. However, we feel that establishing a restoration project in the ETP, where very few coral restoration studies have been undertaken, was necessary within both the ecological and societal approaches. This slow approach to develop responsible practices allow us to expand the effort in a manner that is suitable for both research and effective ecological restoration. One of the biggest challenges in Costa Rica is the demand that is associated with Principle 3; there is a genuine desire among many individuals, businesses, NGOs, and the government to *be part of the solution* to the coral reef crisis, and much of the project's time and effort has necessarily gone toward guidance and training of other coral restoration projects in Costa Rica.

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