SUPPLEMENT

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Coral reefs restoration initiatives in Costa Rica: ten years building hope

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ABSTRACT

Introduction: Costa Rica has been recognized worldwide for its high biodiversity and the conservation actions it has implemented. One of the most iconic ecosystems are coral reefs, which have experienced strong anthropogenic and natural pressures in recent years. To ensure these ecosystems' preservation and services, a series of coral restoration initiatives have emerged in the last ten years along both Pacific and Caribbean coasts.

Objective: To document the different advances of the various coral restoration initiatives Costa Rica's Pacific and Caribbean coasts.

Methods: This review focuses on the implementation of the different reef restoration efforts, indicating the restoration techniques used, the coral species used in the nurseries, as well as the general results of survival and growth.

Results: The first coral restoration project in Costa Rica occurred in the 1990s and was the only such effort until the 2010s. In 2013, a pilot project began in the Golfo Dulce area, which was later replicated in other areas of the country, such as Manuel Antonio, Sámara, and Bahía Culebra on the Pacific coast, and more recently in Punta Cahuita in the Caribbean. Various artificial structures have been used as nurseries in the water column such as trees and ropes, and benthic structures such like A-frames, tables, and spiders, the former being very effective for branching species (*Pocillopora* spp.), while the rest have worked successfully both for branched and massive species (*Pavona* spp. and *Porites* spp.). The results shows a growth rates have been between 6 and 9 cm/year, with survival of 60–90 % of the branching and massive colonies. All sites were seriously affected by the El Niño 2023 phenomenon, with high bleaching values and loss of colonies in the nurseries and on the reef.

Conclusion: Despite geographic and oceanographic distinctions, these projects have emphasized local engagement and perception of coral reefs, fostered intersectoral public-private collaborations for financial and human resources, and operated within established governmental regulatory frameworks. All projects face vulnerabilities such as El Niño events and Harmful Algal Blooms.

Key words: Acropora; Caribbean; El Niño; growth rate; nurseries; Pacific; Pavona; Pocillopora; Porites; survival.

RESUMEN

Iniciativas de restauración de arrecifes de coral en Costa Rica: diez años construyendo esperanza

Introducción: Costa Rica ha sido reconocido mundialmente por su alta biodiversidad y las acciones de conservación que han implementado. Uno de los ecosistemas más icónicos son los arrecifes de coral, los cuales han experimentado fuertes presiones antrópicas y naturales en los últimos años. Para asegurar la preservación de dichos ecosistemas y de sus servicios ecosistémicos, una serie de iniciativas de restauración coralinas han surgido en los últimos diez años a lo largo de ambas costas, Pacífica y Caribe.
Objetivo: Documentar los diferentes avances de las variadas iniciativas de restauración coralinas tanto en la costa Pacífica y Caribe de Costa Rica.
Métodos: Esta revisión bibliográfica se centra en los avances de los diferentes grupos, indicando las técnicas de restauración utilizadas, las especies de coral utilizadas en los viveros, así como los resultados generales de sobrevivencia y crecimiento.
Resultados: El primer proyecto de restauración coralina en Costa Rica se da en la década de los 1990, y fue el único esfuerzo hasta la década de 2010. En el 2013 comienza un proyecto piloto en la zona de Golfo Dulce, que luego se va replicando en otras zonas del país como Manuel Antonio, Sámara, Bahía Culebra, en la costa Pacífica, y más recientemente en Punta Cahuita en el Caribe. Se han utilizado varias estructuras como viveros en la columna de agua como árboles y cuerdas, y bentónicos como marcos en A, mesas, y arañas, siendo estas últimas muy efectivas para especies ramificadas (*Pocillopora* spp.), mientras que el resto han funcionado exitosamente tanto para especies ramificadas como masivas (*Pavona* spp. y *Porites* spp.). En términos generales las tasas de crecimiento han rondado entre 6 y 9 cm/año, con supervivencias entre 60–90 % de las colonias. Todos los sitios fueron gravemente afectados por el fenómeno de El Niño 2023, con altos valores de blanqueamiento y pérdida de colonias en los viveros.
Conclusión: A pesar de las distinciones geográficas y oceanográficas, estos proyectos han enfatizado el compromi- so y la percepción local de los arrecifes de coral, han fomentado colaboraciones público-privadas intersectoriales para recursos financieros y humanos y han operado dentro de marcos regulatorios gubernamentales establecidos. Todos los proyectos enfrentan vulnerabilidades como eventos de El Niño y floraciones de algas nocivas.

Palabras clave: *Acropora*; Caribe; El Niño; Pacífico; *Pavona*; *Pocillopora*; *Porites*; sobrevivencia; tasa de crecimiento; viveros.

INTRODUCTION

Ecological restoration is a series of ongoing activities that seek to conserve biodiversity and human well-being. Within this continuum of activities, ecological restoration is a process that assists in the recovery of an ecosystem that has been degraded, damaged or destroyed (Gann et al., 2019). Coral reef restoration garners attention as human activities and anthropogenic climate change result in an unprecedented scale of reef degradation, compromising ecosystem resilience and survival (Hoegh-Guldberg et al., 2023; Hughes et al., 2018; Suggett et al., 2024). Restoration projects dating back to the early 1980's focused on research and understanding the basics of coral gardening (Bowden-Kerby, 1997; Guzmán, 1991; Guzmán & Cortés, 1989; Harriott & Harrison, 1984; Rinkevich, 1995). In the 2000's, more projects were established as restoration practices were increasingly recognized as a positive tool for reef management and to prevent the extinction of certain coral species such as acroporids in the Caribbean (Lirman & Schopmeyer, 2016; Rodriguez-Martinez et al., 2014; Young et al., 2012). A recent emergence of initiatives occurred after 2016 following El Niño's global scale impact on coral reefs, with special urgency in the Great Barrier Reef (Alvarado et al., 2020; McLeod et al., 2022; Stuart-Smith et al., 2018; Suggett et al., 2019).

Restoration goals and techniques have evolved over the last 20 years. As changing environments modified ecosystem health and composition, new objectives and technologies were required to improve efficiency and holistically tackle the interventions (Mumby et al., 2021; Vardi et al., 2021). Initially, coral restoration was centered on direct coral transplantation and coral gardening, and often neglected the maintenance of species and genetic diversity (Baums et al., 2019; Boström-Einarsson et al., 2020; Rinkevich, 2005). Over time, scientists and coral reef managers suggested a combination of techniques and even, the implementation of higher risk practices, going from genetic and sexual advances (e.g. assisted evolution and coral migration) to socio-ecological interventions, as citizens developing key restoration efforts (Anthony et al., 2017; Hagedorn et al., 2021; Kleypas et al., 2021a; Shaver et al., 2022; Villalobos-Cubero et al., 2023).

In Latin America, reef restoration has been widely practiced in the Caribbean, with less incidence in the Eastern Tropical Pacific (ETP) (Bayraktarov et al., 2020; Bowden-Kerby et al., 2005; Rodriguez-Martinez et al., 2014; Young et al., 2012). Concern for coral reefs' health and the lack of information have motivated more projects in ETP, some with a research purpose, while some others in fact, to assist natural recovery as possible (Bayraktarov et al., 2020; Combillet et al., 2022; Liñán-Cabello et al., 2010; Martínez-Castillo et al., 2023). In recent years, the number of coral restoration efforts in the ETP has increased dramatically (Bayraktarov et al., 2019). However, experience is still limited compared to other regions, such as the Caribbean or the Indo-Pacific (Boström-Einarsson et al., 2020) and few projects use coral gardening (Ishida-Castañeda et al., 2020). Certainly, the Coral Restoration Consortium's lead role has been key to spreading scientific progress and facilitating experience exchange, which is helping new restoration projects stay at the forefront (Vardi et al., 2021). Technology implementation and restoration scale are still a challenge but understanding and coordinating efforts at national and regional levels means an opportunity to connect funds, reefs and challenges (Anthony et al., 2017; Bayraktarov et al., 2020).

With this literature review we wish to recapitulate the advances in the last ten years in the restoration of coral reefs in Costa Rica, both on its Pacific and Caribbean coasts. Our interest is to present a brief account of various artificial reef establishment activities from the 1980s to the present, government support for coral restoration initiatives, and then present the different restoration projects that have been carried out in the last years. We conclude with a series of recommendations and future lines of work at the national and regional level.

Previous restoration initiatives (80 & 90's) in Costa Rica

The first initiatives to restore marine environments in Costa Rica come from the 80's, when an attempt to deploy artificial reefs in the Gulf of Nicoya (Playa Mantas) to provide alternatives for fisheries management (Campos & Guzmán, 1986; Guzman et al., 1988). Using approximately 1 900 tires tied with propylene rope and galvanized wire, an artificial reef was built at 8–10 m depth in modules of 5, 10 and 15 units. Monthly data was collected to compare the fish population versus a natural rocky reef for a year. Throughout this period, the program managers determined that the biomass and number of species of commercial interest were greater than in rocky reefs, being ten times more productive (Campos & Guzman 1986; Guzman et al., 1988). Likewise, they indicated that the artificial reef served as a breeding area for species of commercial value (Campos & Gamboa, 1989; Guzman et al., 1988). By 1987, the reef had 5 000 tires, and they observed a change in the structure of the fish community composition, with a change in dominance from lutjanide to haemulidae. Species of commercial interest represented 47 % of the total species (Campos & Gamboa, 1989). By April 1987, Thorne et al. (1989) investigated the same site to determine the potential use of hydroacoustics for studies of abundance and behavior in artificial reefs. It was possible to detect a strong association of fish with the artificial reef during daylight hours, but a high dispersion during the night.

After this initiative in Playas Mantas, other attempts were made in Bahía Culebra in the 1990s with PVC pipes (J. Campos, personal communication, March 2024), or in various areas of the Gulf of Nicoya with tires (Inter Press Service, 1999), "ReefBalls" (Infobae, 2021; La Nación, 2005; Soto-Méndez, 2021) or shipwrecks (La Nación, 2000; La Nación, 2004). Likewise, the Costa Rican Institute of Electricity (ICE) established an artificial reef with porcelain insulators in Playa Hermosa Guanacaste (Garza, 2019). The most recent initiative comes from the National Learning Institute-Instituto Nacional de Aprendizaje (INA) in Playa Blanca (Punta Leona) using "ReefBalls (Martínez, 2021). All initiatives involved civil society through fishermen's organizations, primary schools or groups of divers, but to date there are no publications or data that quantify their follow-up. Due to this, in 2021, the "Technical guide for the establishment of artificial reefs in Costa Rica" was established, however this guide has not been ratified and made official by the Government. This manual is intended to be a regulatory instrument of the technical processes to be considered in the planning, installation and management projects of artificial reefs in Costa Rica, where the possible implications and responsibilities they entail are clear. Likewise, for 2018, a specific guide was generated for the area of Paquera, in the Gulf of Nicoya (Sánchez & Azofeifa, 2018).

The only coral reef restoration initiative established in that period was performed on the Biological Reserve Isla del Caño, in the southern Pacific of Costa Rica (Guzman, 1991). In response to the impacts of the 1982–1983 El Niño phenomenon and red tides on massive mortalities of the reefs of this island and arguing the low reproductive potential of the corals in the area, Guzman (1991) set out to demonstrate the feasibility of reef restoration. Fifty-two coral fragments of *Pocillopora* were placed on the reef frame by attaching them with wire to 30-cm-long steel stakes and were monitored for almost three years (1987–1989). The results indicated that live coral cover increased from 20 % to nearly 60 %, with a mortality rate of only 20 % on the experimental plot. Likewise, the natural fragmentation produced the appearance of asexual recruits, with an increase of 117 % of new colonies. In this way, Guzman (1991) demonstrated that this type of initiative is feasible in the region under various conservation schemes such as the implementation of the same activity within a marine protected area, and that under the impacts of El Niño, restoration can be a tool to help the recovery of these ecosystems.

The role of the Government in the restoration initiatives

Ecological restoration activities should be conceptualized as a part of governance, which integrates collaborative processes of multiple actors, including the State, the productive sector and society (Richardson & Lefroy, 2016). In these processes, the State can adopt different roles, although often the main contribution is that it is expected to provide the political and legal conditions for restoration initiatives to take place in an articulated and harmonious manner, avoiding conflicts between actors, whether the ecosystem in question is used for consumptive purposes. Flores-Aguilar et al. (2018), when studying cases of environmental governance and payments for environmental services in Latin America, concluded that the State still has an important role in arbitration and allocation of roles among the actors involved. In the case of the policy for "Payment for Environmental Services" (PES) that Costa Rica implemented in the 1990s, this consisted of a system of incentives to landowners for the protection of forests and promotion of reforestation for productive purposes, with results that have been considered very successful. The participating families stated that the PES allowed improvements in the quality of life of the family nucleus, improvement in the environment at the farm and community levels, as well as interpersonal and emotional relationships at the family and personal levels, beyond the thousands of hectares dedicated to the protection of the forest, carbon sequestration and water recharge of these sites (Ortiz-Malavasi, 2004).

In August 2024, the Costa Rican government established Law No. 23555, called "Incentive for the protection of marine-coastal biodiversity." This law establishes the fund for payment for environmental services for marine-coastal ecosystem services, to promote the conservation, sustainable use and restoration of ecosystems located within the territorial sea, as well as the exclusive economic zone of Costa Rica. The groups that can benefit from this fund will be artisanal fishermen, associations, fishing or tourism cooperatives, as well as organized groups within coastal communities that carry out restoration, conservation or sustainable use activities of marine resources. The fund has not yet entered into force and is awaiting the development of the regulations that will put it into operation.

In 2018, an interesting case arose in the implementation of the triangular cooperation project "*Development of an innovative financial mechanism for coral reef conservation in the Dominican Republic*", financed by the Regional Fund for Triangular Cooperation in Latin America and the Caribbean of the German Cooperation Agency (GIZ). In this project, the Dominican Republic, as both the requesting and receiving country, expected to develop a PES mechanism for the conservation of coral reefs, based on the experience in PES for forest protection developed by Costa Rica. During the proposal implementation process, it was identified that there was an opportunity for Costa Rica to receive knowledge transfer and experience in coral reef restoration from the Dominican Republic as part of the same project. Although Costa Rica was already developing some experiences in coral reef restoration, the Dominican Republic's experience in coral gardening became a pivot for Costa Rica for the definition of a country strategy on the subject (Larghi, 2022).

The implementation of this project led to the enactment of Executive Decree No. 41774-MINAE "*Promotion of restoration and conservation initiatives for the recovery of coral ecosystems*", which aims to promote the protection and conservation of reef ecosystems and their associated species throughout the national territory. Under this legal framework and with the implementation of the Costa Rica-Dominican Republic-Germany triangular proposal, implusing the development of coral restoration initiatives in Culebra Bay, Golfo Dulce, Sámara Beach, Manuel Antonio and more recently Southern Caribbean. Under this initiative, knowledge was shared between projects being developed in Costa Rica and coral reef restoration projects in Bayahibe, Dominican Republic, executed by FUNDEMAR and the Center for Marine Innovation of the Punta Cana Group Foundation, both in the Dominican Republic.

Another topic that was considered necessary and developed in this context was a "*Protocol for the restoration of reefs and coral communities in Costa Rica*" (SINAC-GIZ. 2020). This document aims to provide a legal technical guidance framework for coral reef restoration projects in Costa Rica. This guide also arises from the experience of the Dominican Republic in the establishment of coral gardening projects, where the appearance and disappearance of restoration projects sometimes responded to economic rather than environmental interests, which in some cases caused the loss of colonies and the affectation of natural reefs. Ensuring that all restoration projects use a technical and legal basis reduces this risk. This protocol was implemented through a project in which the University of Costa Rica, the NGO Raising Coral Costa Rica, the company Ecodesarrollo Papagayo, the National System of Conservation Areas (SINAC) and GIZ participated. This pilot project consisted of the development of a coral gardening project in Culebra Bay, North Pacific of Costa Rica (see section below).

Finally, following the example of the Dominican Republic, in 2023 the first Coral

Restoration Consortium was established in Costa Rica. This consortium seeks to be a meeting point to discuss the different coral reef restoration initiatives in Costa Rica. The consortium is currently being led by the NGO Raising Coral Costa Rica, and is free adhesion, promoting that to-date is constituted by different national organizations.

Study cases

The studies are presented from north to south on the Pacific side (Fig. 1), without a chronological order, only geographically; while in the Caribbean they only occur in the southern area of said coast. Each geographic area presents its origin, advances and challenges.

Bahía Culebra

The coral reef restoration project in Culebra Bay started in 2019, after a cooperation of more than 20 years between the company Ecodesarrollo Papagayo and CIMAR, and the interaction between the GIZ through its Biodiversity and Business program (DaBio) and the National System of Conservation Areas (SINAC). In addition, the non-profit association Raising Coral Costa Rica joined the initiative to support all the technical knowledge developed in Golfo Dulce. It was decided to work in Culebra Bay due to the great loss of coral cover that the area had suffered in the last decade (Alvarado et al., 2018; Fabregat-Malé & Alvarado, this supplement; Sánchez-Noguera et al., 2018).

The interaction of the academic, private, state, international cooperation, and civil society sectors established the Culebra Reefs Gardens alliance, where the parties cooperate to recover the coral reefs in Culebra Bay and their ecosystem services through ecological restoration. To achieve this objective, a series of activities were proposed, from training of personnel, adequate selection of sites and species, installation of structures that serve as a pilot, continuous monitoring, and evaluating

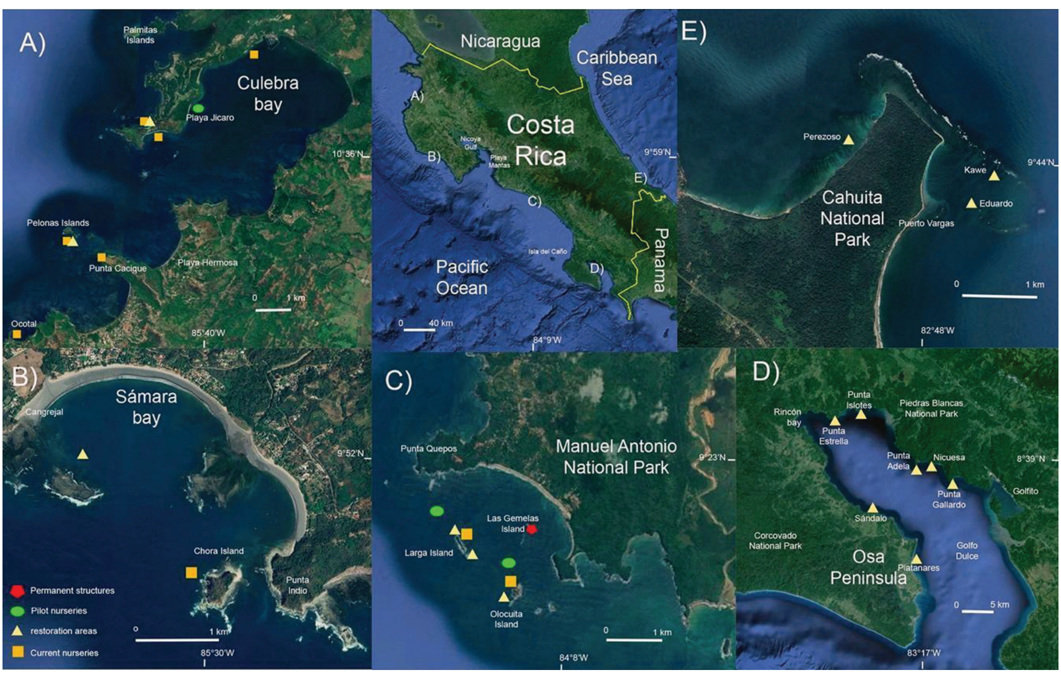

Fig. 1. Location of coral restoration projects in Costa Rica. **A.** Culebra Bay; **B.** Sámara Beach; **C.** Manuel Antonio; **D.** Golfo Dulce; **E.** Punta Cahuita. Orange rectangle: Current nurseries; Yellow triangle: restoration areas; Green ellipse: Pilot nurseries; Red polygon: permanent structures.

how this could be integrated into local responsible tourism activities. Each party has a series of obligations that are related to the activities mentioned above.

A five-year work schedule was established that includes: 1) project planning, 2) the development of a theoretical and practical coral reef restoration workshop with different stakeholders, 3) the installation of nurseries and placement of coral fragments, 4) monitoring and implementation of a coral gardening pilot, and 5) scaling-up the number of nurseries and corals, together with an environmental education program, in parallel with other research such as the analysis of coral reproduction in the nurseries.

Stage one of the project started in April 2019 and stage 2 in August of the same year, and stage 3 started in September with the installation of a ropeline-type nursery and two tree-type nurseries (Fig. 2), both floating, with 585 coral fragments in Playa Jicaro (Fig. 1). In the ropeline the branching coral *Pocillopora* spp. was used, while in the trees the same branching species was used together with the massive corals *Pavona gigantea*, *Pavona clavus*

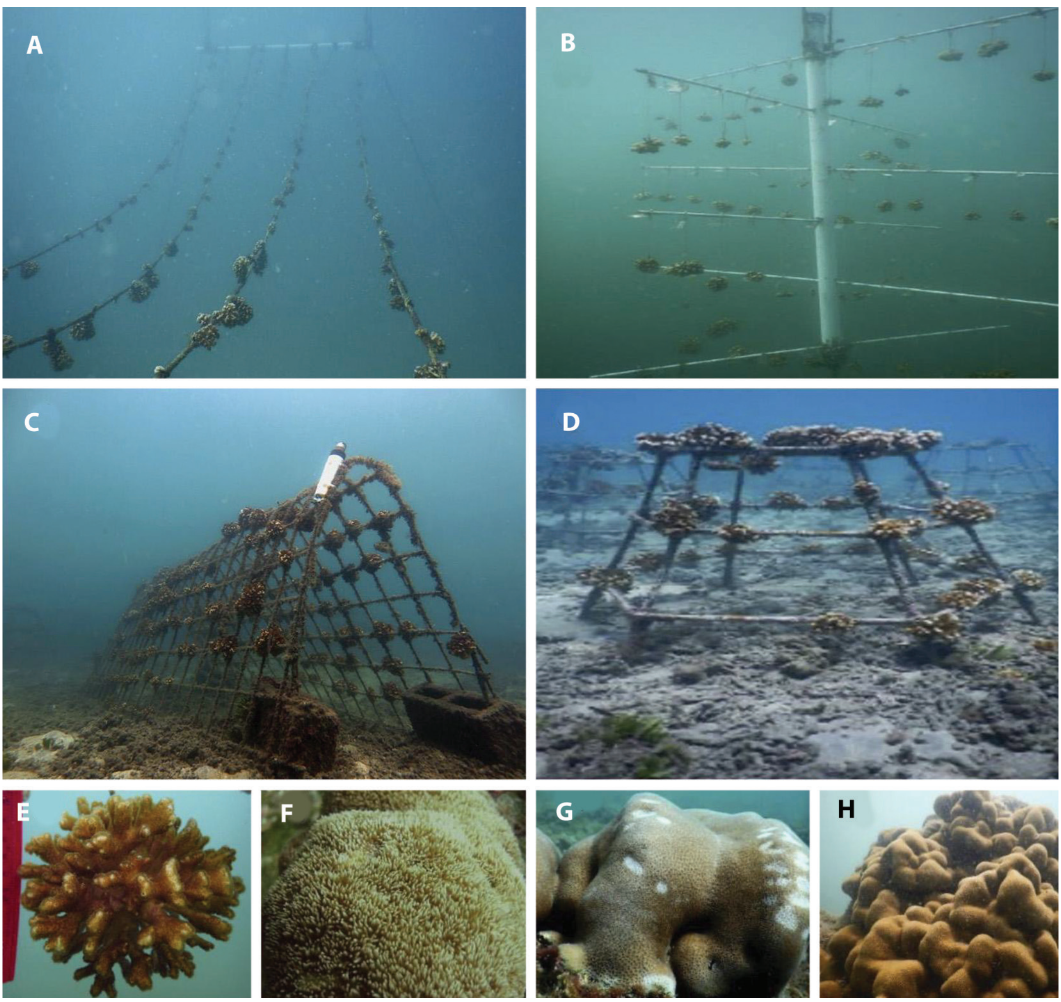

Fig. 2. Nursery types and coral species used in the Culebra Reefs Gardens coral restoration project. **A.** Rope line; **B.** Tree; **C.** A-frame; **D.** Spider; **E.** *Pocillopora* spp.; **F.** *Pavona gigantea*; **G.** *Pavona clavus*; **H.** *Porites lobata*.

and *Porites lobata* (Fig. 2) (Fabregat-Malé et al., 2023). The fragments, from healthy adult colonies, were collected from different points in the bay and in the Gulf of Papagayo. In January 2020, 4 spider-like nurseries were set up with 42 fragments each (Combillet et al., 2022), and in August 2020 two A-frame nurseries were established on the substrate with approximately 400 coral fragments each (Fabregat-Malé, 2022; Fabregat-Malé et al., 2024). Only *Pocillopora* fragments were used in these nurseries. All nurseries were monitored for at least one year, and growth and mortality rates were measured monthly. At the end of this experimental stage in the nurseries, it was determined that maintenance costs were higher in the latter despite the higher growth in the floating nurseries. Likewise, it was quantified that the branched *Pocillopora* species showed greater growth and survival rates than the massive ones. Therefore, it was decided to advance to the next stage of the project used only *Pocillopora* corals in the substrate nurseries. However, it is established as a priority to look for mechanisms to improve the conditions of the massive species.

In this third stage of the project, an experimental planting of 30 colonies of *Pocillopora* spp. and 29 fragments of massive corals (*P. gigantea*, *P. clavus* and *P. lobata*) in a pilot area in Güiri-Güiri (Fig. 1) which had been cultivated in the nurseries at Playa Jícaro in the previous months, was also carried out. For the branching colonies of *Pocillopora* spp., metal rods were driven into the calcareous substrate (former coral framework) to which the transplants were tied employing plastic gauze (Fig. 3). Each of the transplanted colonies was labeled with its own number for later identification during the following months of monitoring. For the massive coral transplants, an underwater drill was used to create holes in the substrate into which the fragments were placed with marine epoxy glue. Over the course of a year, where coral growth, contribution to substrate cover and

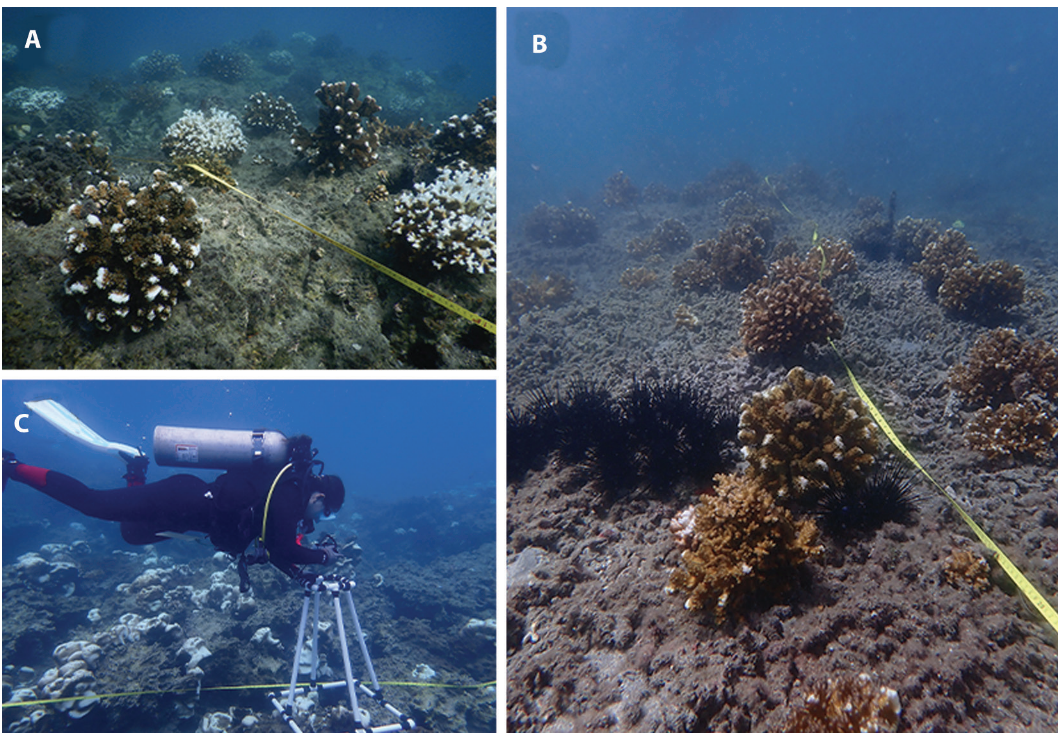

Fig. 3. Transplantation of nursery-grown colonies of *Pocillopora* spp. in **A.** Güiri-Güiri and **B.** Pelonas Islands, Culebra Bay, Gulf of Papagayo. **C.** Monitoring of corals fragments by phototransects.

survival rate were measured (Fabregat-Malé, 2022; Fabregat-Malé et al., 2023). After one year of monitoring, a 100 % survival for *Pocillopora* spp. colonies and 58.62 % for massive corals was determined. The lower survival for the massive growth species probably corresponds to the technique used to perform the transplants, since no dead fragments were observed, but rather a loss of them and of the ceramic disc on which they were glued (Fabregat-Malé et al., 2023). It is important to mention that throughout these three years of research (2019–2021), sea temperature, salinity, and nutrients were constantly monitored.

The fourth stage of the project, scaling up, starts in August 2021 with the increase of sites and nurseries. In Playa Blanca (Fig. 1) 28 spiders and 5 A-frames were placed, in Güiri-Güiri nine spiders were established and in Islas Pelonas five spiders were placed. At the end of that year, in December, the first regional CORALMANIA, a joint activity with Honduras and the Dominican Republic, was carried out contributing to the transplantation of 300 *Pocillopora* colonies of to the Güiri-Güiri reef and 100 to the Pelonas Islands reef. These colonies have been monitored monthly, and an increase in coral cover has been determined in Güiri-Güiri from 4 % to 20 %, and in Pelonas from 5 % to 16 %, as of February 2004 in both sites (Alvarado et al., in prep.). The El Niño 2023 phenomenon strongly affected the colonies, presenting a strong bleaching but rapidly recovering (Alvarado et al., in prep.). Both transplant sites are monitored monthly for fish diversity and abundance, as well as sea urchin (*Diadema mexicanum*), and a gradual increase in the number of fish species has been observed from the beginning of monitoring (November 2021: 20 species) to March 2024 (70 species) (Alvarado et al., in prep.). Currently the project has 134 spiders with at least 7 000 coral fragments growing in the area and is working on the reproduction (histological analysis) results of *Pocillopora* and on the genetic diversity of the coral and their endosymbionts.

As a branch derived from Bahía Culebra's coral restoration project, the Playa Ocotal's restoration program was born, which has a strong social community component as a characteristic feature and can be classified as a collaborative project (Bonney et al., 2009). This initiative has been carried out between the CIMAR and the non-profit association Alianza Mar y Tierra. Alianza Mar y Tierra (AMT) was founded in 2022 to serve as a platform for conservation and restoration projects of terrestrial and marine environments; it's conformed by six members of the board of directors and 32 volunteers who collaborate their programs. Besides Ocotal's coral reef restoration project, the AMT organizes monthly activities such as seabed and beach cleaning, involving dozens of Ocotal and Playas del Coco residents.

Ocotal's coral reef has a common history with others in the North Pacific, in which local and global stressors acted in synergy and led to a devastating reduction in live coral cover (Bezy et al., 2006; Cortés, 2012; Jimenez et al., 2001; Morales-Ramírez et al., 2001; Navarro-Cerdas, 2013; Sánchez-Noguera, 2012) Specifically, in Ocotal a significant increase in the coverage of *Caulerpa sertularioides* and an overgrowth of this alga on the colonies of *Pocillopora* spp. was reported (Fernández-García et al., 2012). Prior to the first intervention on the reef, a visit was carried out where a degraded coral framework was evident, with isolated colonies of massive corals and *Pocillopora* spp. healthy (Fig. 4).

For the intervention on this reef, a citizen science approach has been used; this can be defined as processes in which community members who don't have a formal science education engage in scientific research (Cigliano et al., 2015). In coral reefs, favorable results have been obtained from incorporating of citizen scientists in biological monitoring (Forrester et al., 2015) and ecosystem restoration (Hesley et al., 2017). Ocotal's coral reef restoration project officially began in February 2023 with a community workshop open to the public, resulting in the recruitment of volunteers from outside the AMT. Starting in March 2023, training in biological monitoring of substrate, fish and mobile invertebrates began, as well as the placement and cleaning of structures (Fig. 5).

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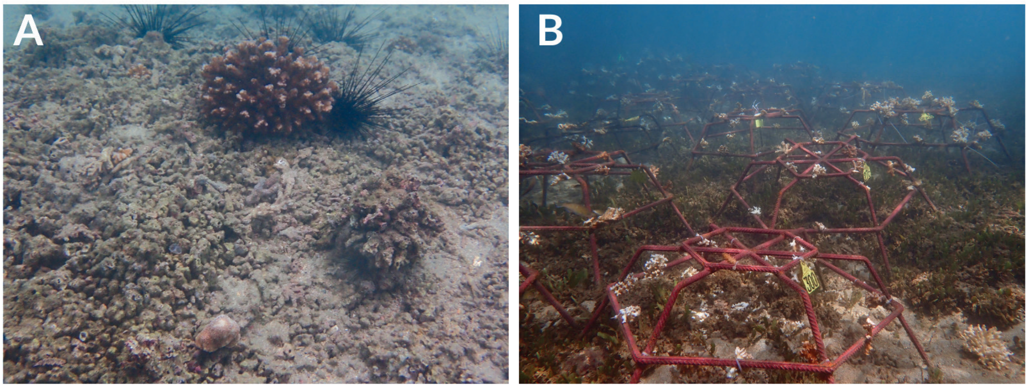

Fig. 4. A. Degraded reef framework prior to the intervention of Ocotal's reef, Gulf of Papagayo (January 2023). **B.** Spider structures used for the restoration of the Ocotal's coral reef (September 2023).

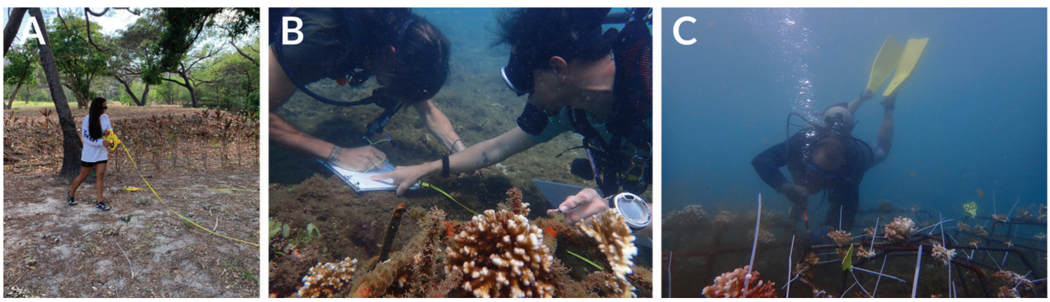

Fig. 5. A. Training carried out on land on biological monitoring methodologies (March, 2023) and **B.** at the restoration point (May, 2023). **C.** Citizen scientist cleaning the structures (May, 2024).

In April 2023, the first 15 structures were placed with fragments from the Jícaro reef and the Playa Blanca restoration point. Thanks to funds from the UCR and private donations, the total number of structures reached 45 by August 2023. In September 2023, a partnership was established with the Costa Rican company Garnier & Garnier Desarrollos Inmobiliarios, which allowed an increase to 65 structures in Ocotal and the intervention of another degraded reef in Punta Cacique. By May 2024, there are 113 structures distributed at the two restoration points, which represents approximately 2 260 living fragments of *Pocillopora* spp.

The inclusion of the human component in the restoration of Ocotal represents a valuable opportunity to include social dimensions, which have been highlighted as essential to ensure the future of coral reefs (Lamont et al., 2022). On the other hand, it serves as an environmental education platform that seeks to improve the relationship that community members have with the marine ecosystems of the region (Dean et al., 2018) and promotes stability over time in this type of projects since there's a reduction in the economic costs associated with restoration process (Hesley et al., 2017).

Samara

Coral reefs in Playa Sámara (Fig. 1) were confirmed to exist through research conducted by Cortés & Guzmán (1998), identifying coral species such as *P. lobata*, *Pocillopora capitata*, *Pocillopora damicornis*, *Porites panamensis*, and *Porites* (*Synarea*) *rus*, this last one being observed only in 1982 and not since. Recently, *Psammocora* spp. was added to this list (Cortés et al., 2010).

The coral reefs in Playa Sámara face significant anthropogenic pressures from sedimentation and pollution (Pereira-Pérez & Mairena-Rodríguez, 2011; Pizzimenti et al., 2011). In response, the Tempisque Conservation Area (ACT) under the Ministry of Environment and Energy (MINAE) enlisted the Instituto Nacional de Aprendizaje (INA) to support a coral reef restoration plan at Playa Sámara, drawing on experience from a similar project initiated in Golfo Dulce in 2013 (Vargas et al., 2020). The goal was to restore ecosystem services crucial for the area's productive tourism and fishing industries.

The project from September 2017 to December 2022 involved monthly coral growth measurements. Work was concentrated on Chora Island, significantly altered by a 7.6 Mw earthquake in 2012, raising its coastline by 0.45 m (Linkimer et al., 2013) and modifying coral community structures vertically and horizontally.

The methodology followed protocols outlined by Edwards & Gómez (2007), Rodríguez et al. (2022), Shafir et al. (2006) and SINAC-GIZ (2020). Initially, the Coral Project Association trained personnel according to the SINAC-GIZ Coral Gardening Protocol, (2020). Exploratory dives off Samara Beach identified coral colonies suitable for restoration efforts, including species from *Pocillopora* spp., *Porites* spp., *Psammocora* spp., and *P. gigantea* (Fig. 6). Different nursery types—platforms, trees, and ropelines (Fig. 7)—were developed based on the Coral Gardening protocol for Costa Rica (SINAC-GIZ, 2020).

Maintenance, monitoring, and cleaning of structures occurred every fifteen days under suitable sea conditions. Growth data, including height, diameter, and colony volume (cm^3) were collected (Robles-Payan et al., 2021). Colonies that doubled in size were transplanted to the Cangrejal area (Fig. 1) within the Bay of Playa Sámara, where ongoing monitoring included assessments of fish diversity and live colony counts, following the PRONAMEC protocol

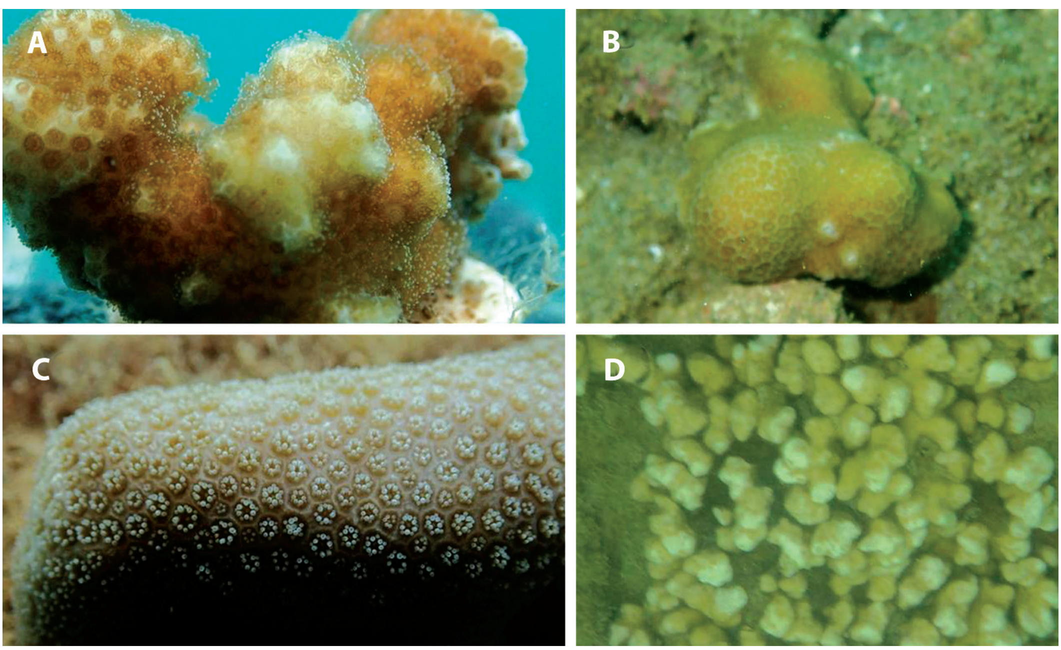

Fig. 6. Coral species found in Samara beach for the coral restoration project: **A.** *Pocillopora* spp., **B.** *Porites* spp., **C.** *Pavona gigantea* and **D.** *Psammocora* spp.

Fig. 7. Gardening coral structures used in Isla Chora of Playa Sámara to carry out the harvest of coral reefs in the Cangrejal sector.

for coral reefs (Sistema Nacional de Áreas de Conservación, [SINAC] 2016).

From 2018 to 2022, 1 404 coral colonies were harvested, totaling 86 610.7 cm^3, with an average width of 2.80 ± 0.07 cm and length of 5.63 ± 0.28 cm. The growth rate over five years was 6.72 cm/year. By species, contributions were 49.7 cm^3 (N = 32) for *P. gigantea*, 372.3 cm^3 (N = 45) for *Psammocora* spp., 1 210 cm^3 (N = 108) for *Porites* spp., and 84 977 cm^3 (N = 1 221) for *Pocillopora* spp. (Fig. 7). Colony loss during harvesting was 15 % due to mortality, detachment, or predation.

Cultivation data indicated rope line structures were most effective, yielding 8 590.2 g/year, followed by trees at 155.64 g/year. *Pocillopora* spp. demonstrated the highest performance, while platforms showed higher mortality rates across all coral species cultured (Fig. 8).

Regarding ichthyofauna in the planting area, 1 131 individuals representing 23 fish species were recorded. *Halichoeres dispilus*, *Thalassoma lucasanum*, and *Abudefduf troschelii* were the most abundant, alongside various invertebrates and vertebrates. In 2023, during the El Niño phenomenon, 77 coral colonies were surveyed in the transplant area, with 21 affected by bleaching.

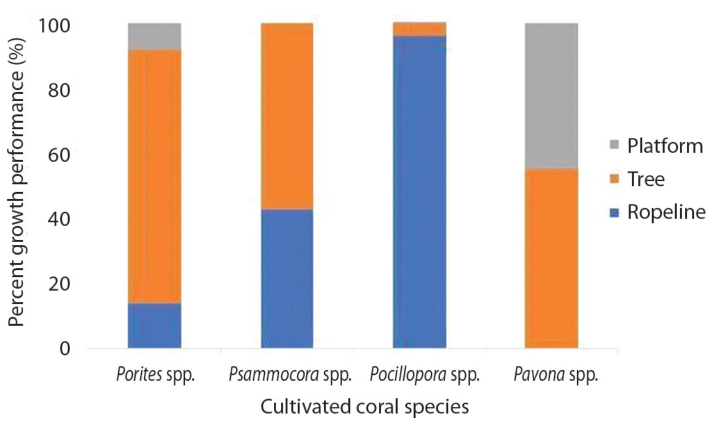

Fig. 8. Coral species grow in three types of gardening in the middle of the water column on Chora Island of Samara Beach. The trend is that branched or sub-branched species grow better on antenna and clothesline, while massive or sub-massive species grow better on the platform or antenna.

The results of coral restoration efforts in Sámara align with findings from Vargas et al. (2020) and Rodríguez et al. (2022), emphasizing the success of branched or sub-branched species. The total volume produced from 2018 to 2022, 86 610.7 cm^3, is comparable to results from Robles-Payan et al. (2021) over 396 days, highlighting the need for improved production efficiency. Hanging structures like ropelines and trees proved effective for branched species such as *Pocillopora* spp., whereas platforms were suitable for massive species like *Porites* spp.

Manuel Antonio

Marine Conservation Costa Rica (MCCR), a non-profit organization, was founded in 2019 by biologists and dive professionals from the Oceans Unlimited Dive Center in Quepos (Fig. 1), on Costa Rica's central Pacific coast. In the same year, the organization received permission from the SINAC to initiate a pilot study on coral reef restoration in Manuel Antonio, which houses the renowned Manuel Antonio National Park (MANP). As the largest marine protected area on mainland Costa Rica, this region was selected due to its historical focus on terrestrial conservation, while its coral reefs have suffered degradation over decades from various local stressors such as river runoff, sedimentation, and agricultural and domestic contamination (Sistema Nacional de Áreas de Conservación, 2013). The project involves contributions from the founding members, core staff biologists, trained volunteers, international interns, and local community divers.

Following a planning period that included surveys for reefs and nursery sites, the pilot study started in April 2019. Initially, four nursery sites were chosen: two on the inshore sides of islands, which offered greater wave protection, and two more on exposed sites (Fig. 1). Due to the high-water movement in the area, fixed table structures were selected for the nurseries. Initially, large nursery tables made from PVC tubing were used (Fig. 9A). However, after several months in high-energy environments, these were scaled down to smaller, more robust table structures (Fig. 9B). Nurseries were installed at each of the four sites, at depths of 10–12 m to avoid the shallow surge.

In June 2019, the next phase of the pilot study involved adding coral fragments to the nurseries, starting with *Pocillopora* spp. and *P. gigantea*, followed shortly by *P. lobata*, with 15 samples of each coral species at each site. By early 2020, the focus shifted to expanding the

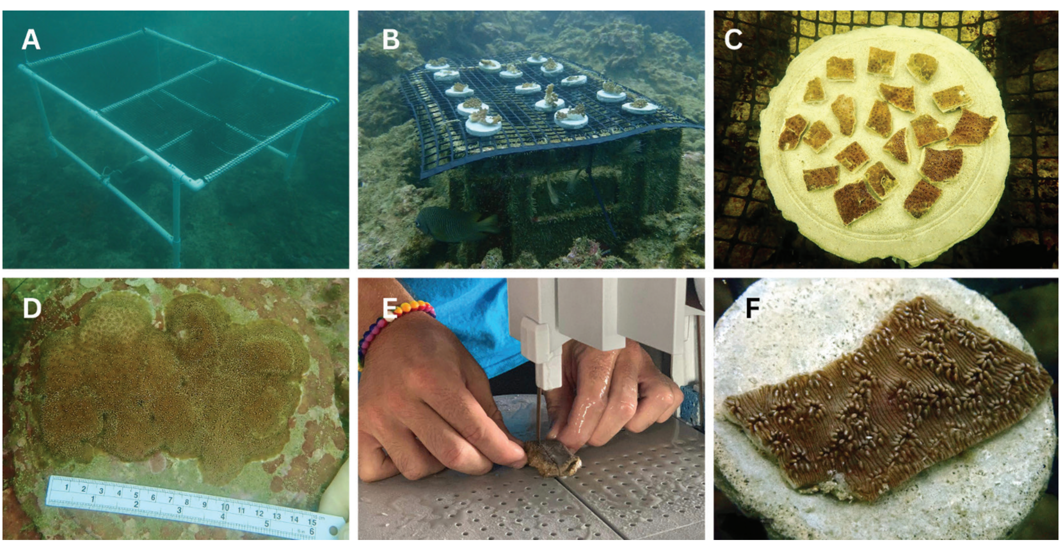

Fig. 9. A. Original table nursery, **B.** Small table nursery, **C-D.** Coral fusion techniques, **E-F.** Coral fragmenting techniques.

more protected nursery sites, and in July 2020, the first coral colonies were outplanted to the restoration site north of Isla Larga (Fig. 1).

The restoration project has expanded significantly from 2011 to 2024. As of April 2024, there are 36 nursery structures. Following the success of *Pavona gigantea*, restoration efforts have included *Pavona frondifera* and *Pavona duerdeni*. In 2022, the project adopted the coral fusion method (Fig. 9C, Fig. 9D), where fragments of the same genotype coral are adhered to a plate to fuse and reform larger colonies, facilitating faster growth and maturity before outplanting. This method has been tested successfully with *Pocillopora* spp., *P. frondifera*, and *P. gigantea*, except for *P. lobata*, which did not compete well against algal growth.

The project has faced various challenges, necessitating adaptations in methodology, often with advice from other restoration groups in Costa Rica. Key issues and responses include: 1) Algal Growth: Coral fragments are cut to 2-3 cm to better compete against algal growth (Fig. 9E, Fig. 9F); 2) Sustainability and Plastic Use: Initially, coral fragments were attached using plastic wall plugs and zip ties (Fig. 10A). In 2021, the project began producing custom discs with posts made from natural sand and cement, minimizing plastic use and eliminating plastic at outplanting sites (Fig. 10B). The current nursery structures utilize repurposed durable plastic crates, originally used for delivering produce in the food industry. These crates, which would otherwise be discarded and end up in landfills, are reused in our project, thereby extending their lifecycle. Additionally, the crates are economical, easy to install and relocate as needed; 3) Water Movement: Custom-made coral posts snugly fit into nursery meshes (Fig. 10C) and are secured to the reef using marine epoxy (Fig. 10D). Nursery structures are weighed with cement blocks and anchored with metal pins; 4) Red Tides: In 2022, reduced growth was observed due to prolonged red tide presence. Harvesting and fragmentation of *P. lobata* was halted for one year due to its susceptibility to reduced water quality; 5) High Water Temperatures: During the 2023 El Niño event, high water temperatures caused bleaching in shallow outplanted corals (< 8 m depth) and partial bleaching in nurseries (10–12m depth). Fragmenting and outplanting were paused due to concerns abbout additional stress to the corals, and resistant wild colonies were identified for future harvesting.

As of April 2024, there are 700 fragments in the two nursery sites. Coral fragments typically remain in nurseries for 6–12 months before

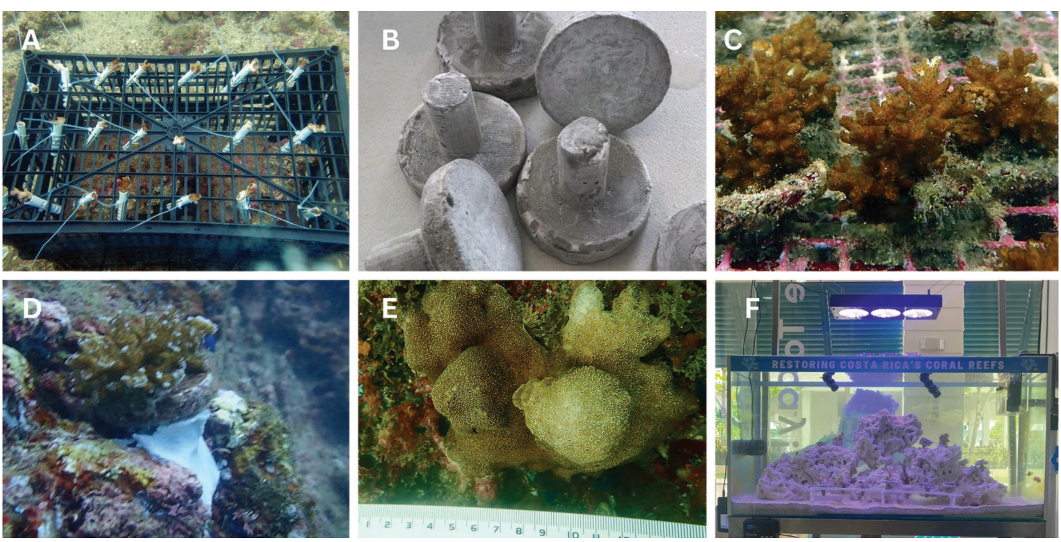

Fig. 10. A-C. Nursery attachment techniques, **D-E.** Coral outplants, **F.** Coral tank.

outplanting. Due to refined methodologies, survival rates have improved from 70–80 % to over 90 %. Post-outplanting survival is approximately 95 % (Fig. 10E) with most losses due to algal overgrowth. Over the past four years, 1 750 corals have been outplanted. Monitoring from January 2019 to January 2024 has shown an increase in fish species from 18 to 31 and an increase in coral cover from 1 % to over 3 %.

The project's future goals include significantly increasing outplanting numbers, aiming to add thousands of new colonies annually. As part of our restoration project, we are establishing a coral tank in May 2024 (Fig. 10F) to hold corals before transferring them to the nurseries and to educate the community on coral reefs and restoration. Additionally, this provides an opportunity to explore techniques for potentially utilizing ex-situ tanks to enhance the production of coral colonies.

MCCR has received permission from SINAC to install permanent reef structures in Manuel Antonio Bay to alleviate pressure on popular snorkel sites and serve as educational tools for coral conservation. This project, delayed due to funding issues, is set to begin in late 2024.

Golfo Dulce

Golfo Dulce (Fig. 1) has been a site of coral reef restoration for nearly a decade, as part of an effort to (1) rehabilitate coral reefs that had been severely impacted by sedimentation and (2) to do so in ways that promote resilience of the reefs to climate change.

Beginning in 1990, Cortés (1990a), Cortés (1990b) and Cortés (1992) documented how sedimentation associated with logging of the rainforest and road construction had likely caused severe degradation of most of the coral reefs in the gulf, and the rarity of *Pocillopora*, particularly in comparison with other Pacific coast reefs of Costa Rica. Following government actions to halt the logging and other causes of sedimentation, water quality improved and coral reefs showed signs of recovery, and Cortés (1992) suggested that Golfo Dulce would benefit from coral propagation and reef restoration.

The first attempt to propagate corals in Golfo Dulce was initiated in 2014 by the INA. They placed a mid-water platform structure for coral propagation at about 8 m depth near Playa Nicuesa (Fig. 1). They deployed 70 fragments of *Porites lobata*, *Pavona varians* and *Psammocora stellata* and demonstrated good growth of the fragments over the following 17 months (Vargas et al., 2020), although the *P. lobata* and *P. varians* fragments died after eight months, which the authors correlate with the presence of a red tide. INA has continued the deployment of coral propagation structures in several other locations in the Gulf, and over time propagated and outplanted coral fragments at multiple sites.

In 2016, once corals recovered following a bleaching event that caused significant mortality in Golfo Dulce (Alvarado et al., 2020), researchers and students from the University of Costa Rica installed two mid-water tree structures, also near Playa Nicuesa, to pilot test the efficacy of coral propagation and outplanting methods in the gulf, as well as the knowledge and perceptions of residents about coral reefs (Villalobos-Cubero et al., 2023). The latter was a major part of the restoration effort, following the philosophy of Suding et al. (2015) hat outlined the four main components of successful restoration programs, including not only 1) assessment of the sites environmental past and future, 2) consideration of the ecological principles, and 3) commitment to sustained effort, but also 4) strong engagement of local communities. Raising Coral has invested in local communities of Golfo Dulce primarily through a coral gardener training and employment program that includes 20 local people, but also through active engagement of local government officials and the public, with a network of over 60 national and international allies.

Initially, fragments of *Porites evermanni/lobata*, *P. gigantea*, and *Pocillopora* spp. were propagated, outplanted and monitored for several years, testing species responses to a variety of techniques (Kleypas et al., 2021b;

Villalobos-Cubero, 2019). In 2019 the project evolved into a formal effort with the establishment of the NGO Raising Coral Costa Rica, and operations gradually expanded to include more structures (currently 11 trees, five rope nurseries, Fig. 11) with a capacity of nearly 2000 coral fragments. In 2021, Raising Coral became an official user of the Mars reef restoration system (MARRS; Smith et al., 2021) and has so far deployed 95 reef stars with a total capacity of about 1 400 fragments. Since the start of the project, all donor coral colonies have been marked in the field and all fragments and outplanted colonies have been tracked with a donor ID, except when using fragments of opportunity or when sampling *Psammocora stellata*, which at some sites exhibits a growth habit of loosely interlocking benthic cover rather than distinct colonies.

Raising Coral works with the 9 reef-building coral species in Golfo Dulce, but so far has focused on rebuilding the populations of

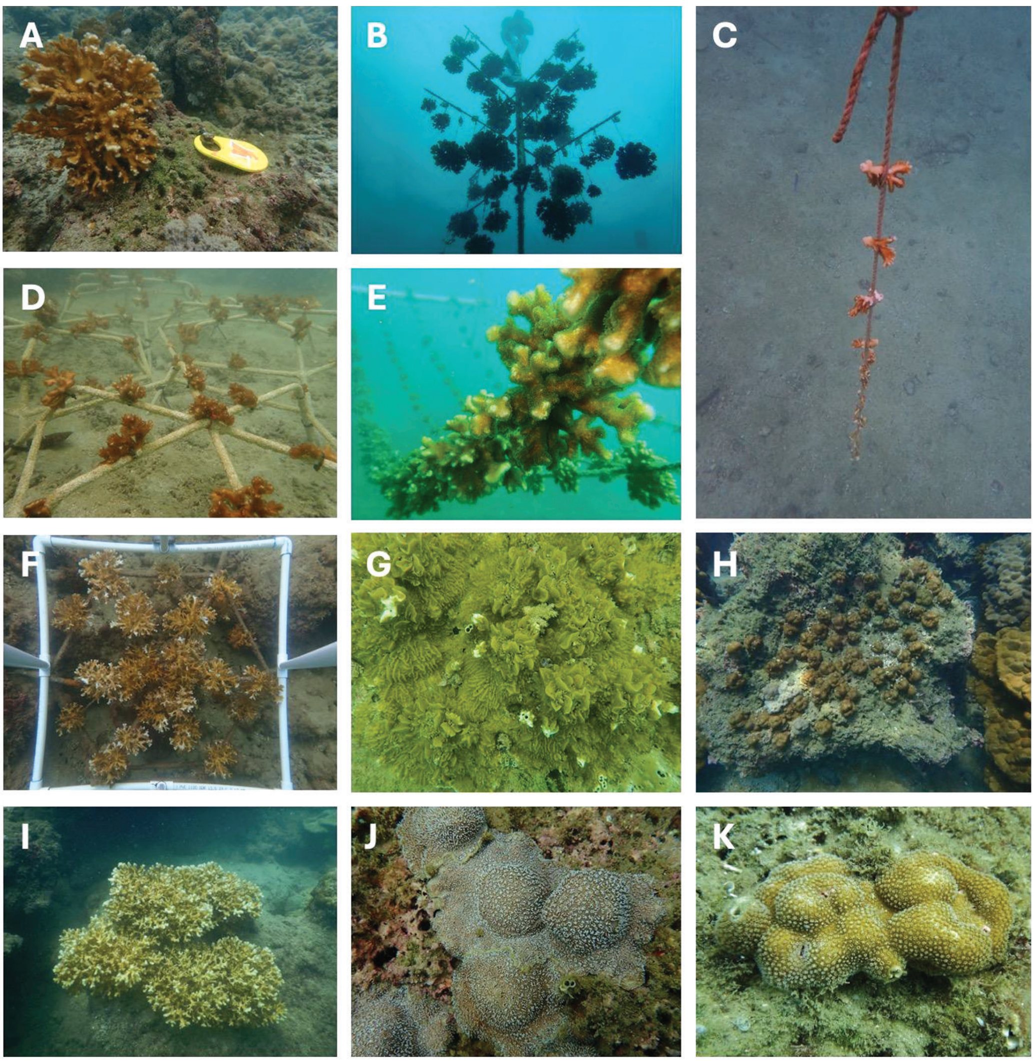

Fig. 11. Propagation and outplanting techniques at the Golfo Dulce site. **A.** donor colony of *Pocillopora* spp.; **B.** midwater trees; **C.** vertical rope (experimental); **D.** MARRS reef stars; **E.** rope nurseries; **F.** monitoring of *Pocillopora* spp. on reef stars; **G.** propagated colony of *Pavona frondifera*; **H.** direct outplants of *Porites* spp. to “reskin” older *Porites* surface; **I.** cluster of fused *Pocillopora* spp. Outplants; **J.** fused outplants of *Pavona gigantea*; **K.** fused outplants of *Porites* spp.

Pocillopora species in Golfo Dulce. *Pocillopora* colonies were rare in Golfo Dulce in 2016, and in fact, over the course of several years fewer than 20 natural colonies were encountered that were large enough to sample for propagation. Most of these were found in waters between 7–12 m deep, except for several large *Pocillopora* colonies and recruits found at much shallower depths. Fragments of *Pocillopora* (1–2 cm in length) grew well in every type of structure to outplantable colonies of 10–14 cm diameter in 8–12 months. Before outplanting, several fragments were obtained from each colony to continue the propagation in the nursery.

Over time, about 3000 thousand *Pocillopora* colonies were propagated and outplanted in multiple areas, with the majority at the northernmost reef sites of Golfo Dulce. The outplanting design included placing 8–15 clonal colonies in patches to increase the probability of colony fusion, and then arranging patches to maximize cross-fertilization amongst different donors. The colonization of some of the first outplanted colonies of *Pocillopora* by cryptofauna was investigated by Chomitz et al. (2023a) and Chomitz et al. (2023b).

The number of propagated and outplanted *Pocillopora* colonies grew progressively through early 2023, with interruptions caused by harmful algal blooms ("red tides") and bleaching. Red tides became increasingly common over that period and particularly in late 2020, causing the mortality of 11 % of the *Pocillopora* fragments in the nursery; despite this event by 2022, the average survival percentage for nursery fragments was 98 %, and outplants survival was 94 %. Later, in early 2023, a red tide followed by a record marine heat wave caused the mortality of 90–95 % of the *Pocillopora* colonies, particularly outplants at shallower depths. Coral fragments in the MARRS structures survived best, likely due to multiple factors (Sandoval et al., 2022).

The timeline of the restoration effort in Golfo Dulce provides an example for sustaining corals and reefs in a warming world (Fig. 12), i.e., planning for expected setbacks due to environmental threats such as harmful algal

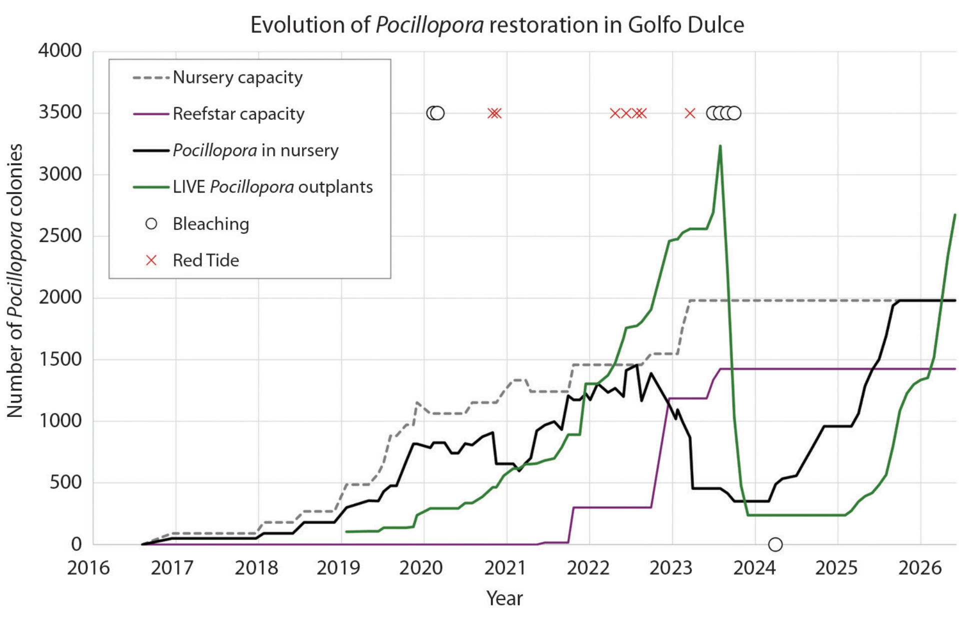

Fig. 12. Changes in the Raising Coral nursery capacity (not including fragments deployed using MARRS), number of *Pocillopora* fragments in propagation, and total number of *Pocillopora* outplants between 2016 and 2024. Projected values are shown through June 2026, using modest rates of *Pocillopora* propagation.

blooms and climate change (as well as coral disease). Unlike in other Pacific case studies in Costa Rica, the slow start to *Pocillopora* propagation was hindered by the rarity of colonies large enough for fragmenting and a small team and nursery capacity. Over time, the capacity and efficiency of propagation and outplanting steadily increased, and despite the severe mortality of 2023, the ability to recover over the next two years is now greatly enhanced by (1) the fact that there are still more colonies of *Pocillopora* than when the project began, (2) an existing large nursery capacity, and (3) the experience of the community members working as coral gardeners, which greatly increases the efficiency of the work. Our team also found that the survival and growth of some species improve when fragments are propagated directly on the reef rather than in a nursery (Sandoval et al., 2022). Tracking fragments by donor has also yielded useful information, such as identifying genotypes that are more resistant to bleaching or more likely to recover following bleaching. In anticipation of the 2023 bleaching event, Raising Coral implemented a Coral Bleaching Contingency Plan that included several actions to minimize coral loss: lowering structures in the nursery, shading experiments, and mainly distributing fragments from each of the *Pocillopora* genotypes across a wide array of sites. Such *in situ* coral banking is a good alternative when *ex situ* coral banks are not available, and at the same time helps identify locations that can serve as coral refugia during future marine heat waves.

Southern Caribbean

Coral reef restoration in Costa Rica's Southern Caribbean began in 2021, driven by the interest of Cahuita's National Park marine management program in assessing the viability of coral restoration techniques as a management tool to achieve their conservation goals. These goals include (1) conserving an ecologically representative sample of Caribbean reef and seagrass systems, along with their associated fauna and flora, and (2) contributing to adaptation and mitigation measures for marine and coastal biodiversity in response to the impacts of climate change in the Costa Rican Caribbean. Consequently, Raising Coral Costa Rica and ACLAC-SINAC established a joint restoration project.

The reef system at Cahuita National Park (PNC) (Fig. 1) is the most developed and extensive (600 ha) reef habitat in the country, yet it is also one of the most deteriorated and threatened. Since the early 1980s, Jorge Cortés and colleagues have documented a significant decline in live coral cover, from a baseline of 40 % in the early 1980s to just 10 % in the early 1990s (Cortés, 1994; Cortés et al., 2010). This decline is primarily attributed to sustained nutrient runoff, high sedimentation stress, and the deleterious effects of bleaching events over the years, notably in 1983, 1992, 1995, 1998, 2005 (Cortés, 2016; Cortés & Jimenez, 2003a; Cortés et al., 2010; Jiménez, 2001), and 2020, 2023 (Quezada-Perez et al., 2023).

More recently, Quezada-Perez et al. (2023) reported around 12–25 % reef cover, which is significantly lower than the original baseline but somewhat higher than in the 1990s. The same study found an increasing trend in algae cover, rising from 37 % in 2003 to 70–73 % in 2023. These findings suggest a potential phase shift from a coral-dominated reef to an algae-dominated reef. This shift results in low levels of key ecological indicators, such as fish diversity and reef rugosity, leading to the loss of critical ecosystem services.

These circumstances underscore the necessity for sustained implementation of resilience-based coral restoration efforts, which aim to reduce stressors to reefs and enhance ecological and social processes that improve Costa Rica's Caribbean reef health, as Cortés (2016) and Cortés et al. (2010) stated.

As of April 2021, three types of nurseries were established and tested for the growth and survivorship of reef-building species: symmetrical brain coral (*Pseudodiploria strigosa*), fused staghorn (*Acropora prolifera*), and endangered elk horn (*Acropora palmata*). The nurseries included tree-like and rope-type structures for the branching *A. prolifera* and a mid-water floating platform for culturing the massive *P. strigos*a. *Acropora palmata* fragments were tested in both the tree and platform nurseries (Fig. 12). These nurseries were installed at depths of 2–4 m, with fragments sourced from donor colonies selected from different reef habitats. Sea surface temperature was recorded using autonomous HOBO data loggers and the Aqualink Sofar Buoy. Trained SINAC officials and volunteers played a critical role, assisting with nursery maintenance and fragment monitoring. Survival rates varied between species and cultivation techniques. For *A. palmata*, fragments placed on tree structures showed survival rates ranging from 56 % to 100 %, depending on the donor colony. Notably, fragments from colony D1 exhibited 100% survival on the tree structure and 38.5 % when placed on "cement cookies" in the platform, likely due to sedimentation stress based on observations of sediment accumulation on the exposed area of the cement cookies. In contrast, *P. strigosa* fragments achieved 100 % survival in the platform structure. *Acropora prolifera* fragments had survival rates of 90 % on tree structures and 100 % on rope nurseries. On platforms, *A. palmata* fragments grew from 38 cm² to 46.9 cm² (Δ8.9 cm²/0.06 cm² day^{-1}), while on the tree nursery they grew from 48.9 cm² to 72.8 cm² (Δ23.8 cm² /0.18 cm² day^{-1}). *Pseudodiploria strigosa* grew from 20.07 cm² to 21.29 cm² (Δ1.02 cm²/0.007 cm² day^{-1}), reflecting their slower growth rates. In the case of *A. prolifera* fragments on ropes grew from 9.6 cm to 25.4 cm (Δ15.8 cm/0.12 cm day^{-1}) in linear tissue extension, while those on tree branches grew from 7.2 cm to 26.8 cm (Δ19.6/0.15 cm day^{-1}), confirming their rapid growth potential (Lirman et al., 2010) (Fig. 13).

Building upon these initial results, during the rest of 2022 and early 2023, more coral trees were placed, the size and material of the cookies were reduced, and rope nurseries were installed among the remaining pilings of an old pier near the Perezoso area (Fig. 1), with a capacity to produce between 600–1 200 fragments. However, despite the positive response of the fragments to the cultivation techniques, modifications had to be made to the cultivation strategy and project management. Given Costa Rica's high wave conditions in the Caribbean (Lizano, 2007), mid-water floating structures suffered structural damage. Therefore, fixed structures to the bottom, such as reef-stars frames, were tested. Concurrently, an adaptive management model was adopted, enabling a flexible decision-making strategy incorporating experimentation, monitoring, and iteration, allowing the opportunity to adjust over time and deal with uncertainties (Anthony et al., 2015; McLeod et al., 2019).

Several trials are conducted to determine the most cost-effective outplanting technique suited for site conditions before initiating mass outplanting. In June 2022, a pilot outplanting of four clonal micro-fragments (~ 5 cm²) of *A. palmata* was conducted, utilizing nursery-grown fragments initially harvested from donor colony D14 at Kawe (Fig. 1) (Papke et al., 2021). The outplanting took place at the Eduardo reef patch (9°44'15.2"N, 82° 48' 21.4"W). By December 2023, the fused basal area of the fragments had expanded by over 1 000 %, growing from 19.25 cm² to 213.2 cm² (Δ 193.95 cm²/0.35 cm² day^{-1}). Notably, both the outplanted fragments and their parental colony remained unaffected by the 2023 bleaching event, suggesting that the bleaching resilience of donor colony D14 is a stable trait that persists through the culture process and transplantation to a new site (Anthony et al., 2015; Baums et al., 2019).

In early September 2022, a reef-star cluster (N = 4) was deployed at the Kawe site, holding 49 fragments of *A.* palmata and 18 fragments of *A. prolifera*. Almost a year later, by August 2023, *A. palmata* fragments had increased 2.4-fold in size, growing from 28 cm² to 68 cm² (Δ 40 cm²/0.11 cm² day^{-1}). Similarly, *A. prolifera* fragments grew from 10 cm² to 46 cm² during the same period (Δ 36 cm²/0.10 cm² day^{-1}). Prior to the 2023 bleaching event, the corals exhibited a 100 % survival rate. However, following the event, survival rates decreased to 46 % for *A. palmata* and 44 % for *A. prolifera* (Fig. 14). These observations highlight the

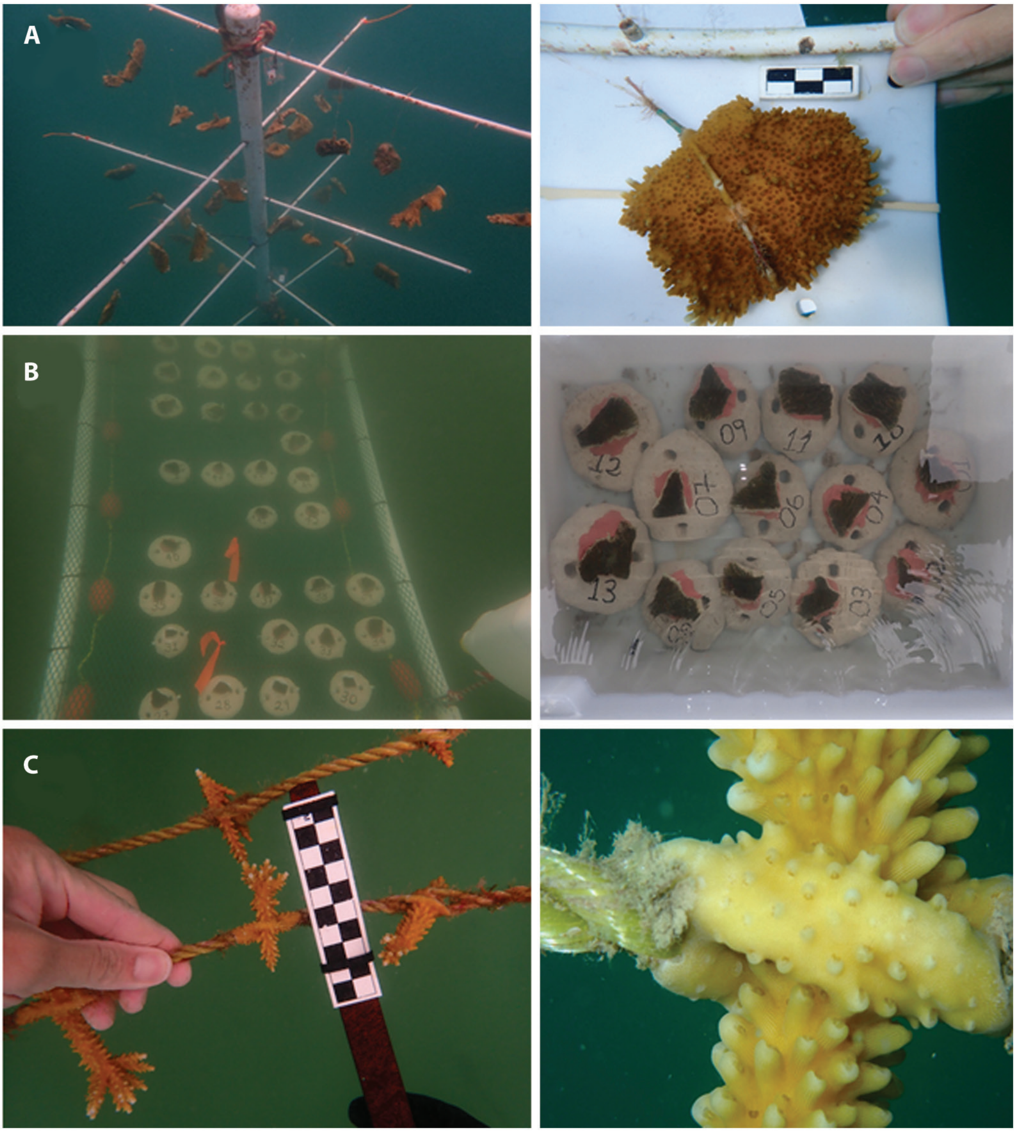

Fig. 13. Nursery types and growth of different coral species. **A.** Tree structure with a detailed view of an *Acropora palmata* fragment; **B.** Platform structure with a detailed view of *Pseudodiploria strigosa* fragments; and **C.** Section of a clothesline with a detailed view of an *Acropora prolifera* fragment growing on the rope.

initial success of the reef-star method in promoting coral growth and survival, though the notable reduction in survival rates post-bleaching event underscores the vulnerability of these coral species to thermal stress.

Later that same month (September 2022), 10 fragments of *A. prolifera* were outplanted in the Puerto Vargas sector. Small fragments (< 4 cm^2) were adhered to the substrate using a nail and a plastic zip tie. By April 2024, the fragments on average had grown from 2.15 cm^2 to 23.26 cm^2, reflecting an increase of 21.11 cm^2 (0.04 cm^2 day^{-1}). Survival rate of the fragments after year one was 80 %.

Coral spawning observations were conducted around Cahuita, Punta Uva, and

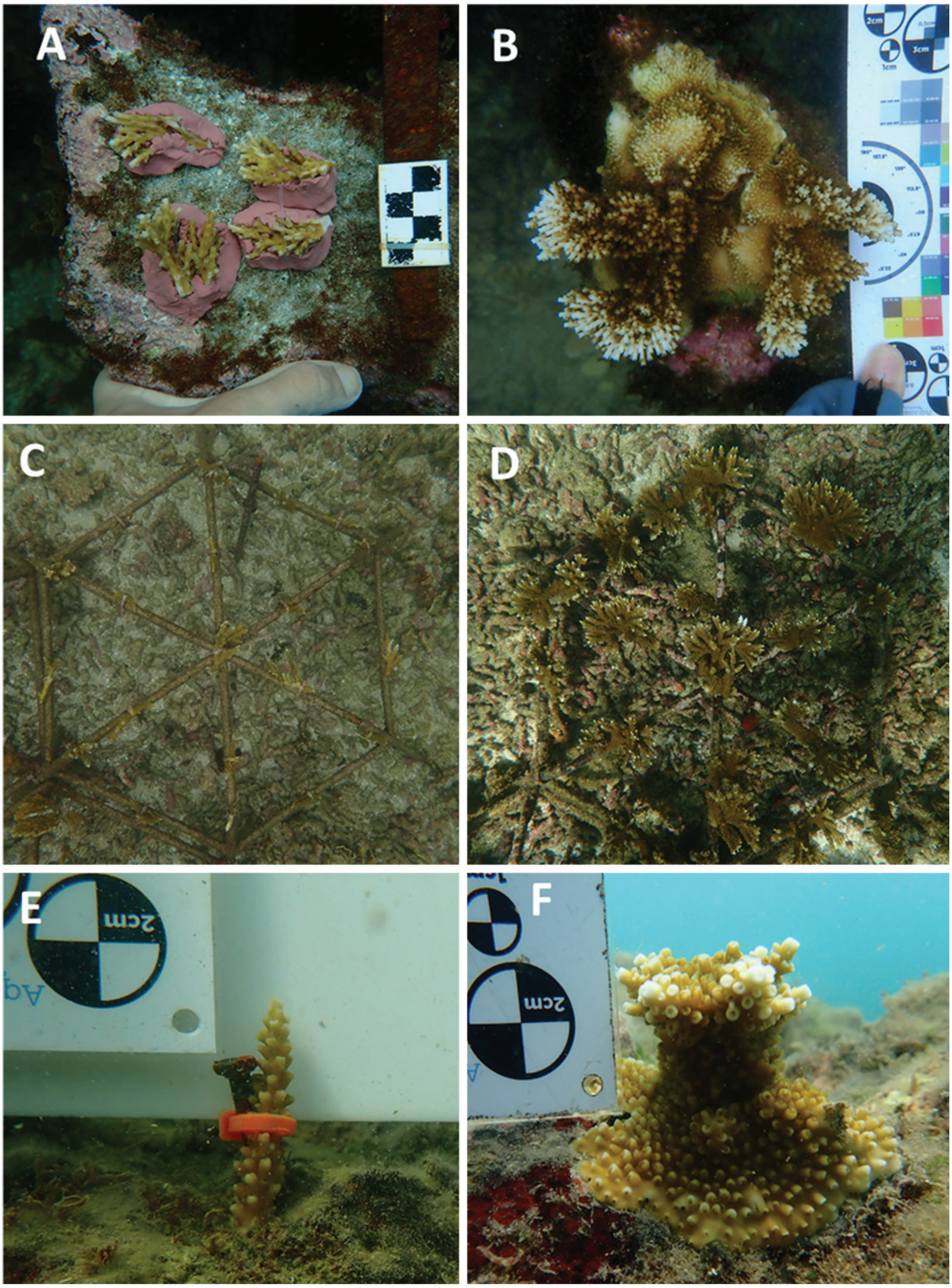

Fig. 14. Outplanting techniques tested in 2022–2023 at Cahuita site. **A.** *A. palmata* microfragments attached to substrate with marine epoxy, **B.** same fragments fused and developing protobranches, **C.** fragments of *A. prolifera* placed at Kawe reef star cluster, **D.** same fragments showing growth over the structure, **E.** an *A. prolifera* fragment attached to the substrate using nail and zip tide, **F.** the same fragment showing positive growth.

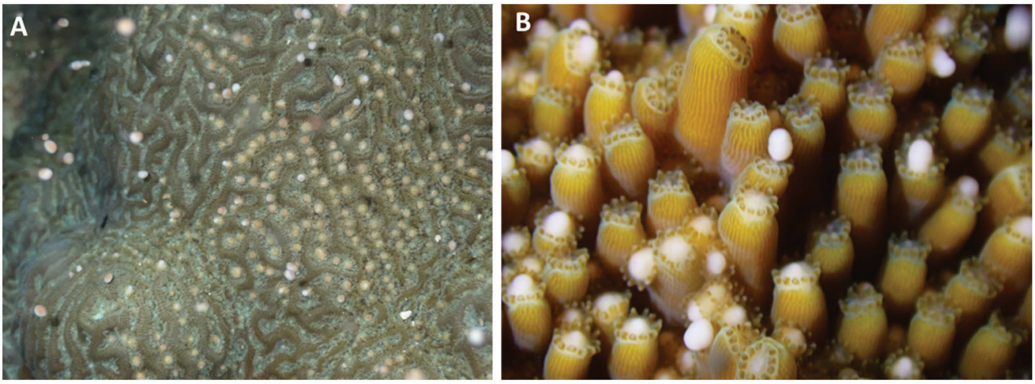

Fig. 15. Spawning observations during the project's lifespan. **A.** *P. strigosa* releasing gamete bundles in Cahuita National Park in August 2021, **B.** *A. palmata* releasing gamete bundles in Manzanillo in September 2023.

Manzanillo from 2022 to 2023. *Pseudodiploria strigosa* was observed to spawn in August 2022 in Cahuita and in September 2023 in both Punta Uva and Manzanillo. *Acropora palmata* was also observed to spawn in September 2023 in both Punta Uva and Manzanillo (Fig. 15). These observations are significant as they mark the initial step towards studying the reproductive activity of reef-building corals and the potential application of assisted sexual reproduction techniques in the Costa Rican Caribbean.

The 2023 bleaching event significantly impacted both the reef and restoration efforts, reducing the amount of propagative material available for transplantation by approximately 40 %. Currently, efforts are focused on replenishing coral nurseries and increasing the frequency of transplantation. These efforts incorporate lessons learned during the contingency plan implemented before and during the bleaching event. For instance, there is now an emphasis on including coral colonies that demonstrated resistance to bleaching or exhibited a high recovery rate post-event. Continued research and community involvement are essential to sustaining and scaling these efforts and achieving long-term conservation goals in the face of ongoing environmental challenges.

Challenges, future needs and concluding remarks

Over nearly a decade of coral restoration efforts in Costa Rica, work has spanned virtually all coral regions across the country (Cortés & Jiménez, 2003a; Cortés & Jimenez, 2003b). Initiatives have covered diverse areas from the coastal upwelling zones in the northern Pacific to the thermally stable environments of the South Pacific and Caribbean. Restoration efforts have focused on ten coral species, seven in the Pacific (*Pavona clavus*, *Pavona gigantea*, *Pavona frondifera*, *Pavona duerdeni*, *Porites lobata/evermanni*, *Psammocora stellata*, and *Pocillopora* spp.) and three in the Caribbean (*Acropora palmata*, *Acropora prolifera*, and *Pseudiploria strigosa*), with notable success observed in branched species like *Pocillopora*. However, challenges persist with massive coral species, particularly concerning nursery and transplant survival rates. Various types of nurseries, including both water-column and substrate-attached designs, have been utilized successfully, tailored to the specific oceanographic conditions of each site. This has resulted in managing nearly 19 000 coral fragments across nurseries and transplant areas throughout the project's duration.

Despite geographic and oceanographic distinctions, common factors have characterized these projects. They have emphasized local engagement and perception of coral reefs, fostered intersectoral public-private collaborations for financial and human resources, and operated within established governmental regulatory frameworks conducive to restoration efforts (Palou-Zuñiga et al., 2023). All projects face vulnerabilities such as extreme temperature variations from El Niño events and detrimental impacts of algal blooms, significantly affecting coral fragment survival in nurseries.

To enhance conditions at coral reefs and restoration sites, urgent measures include mapping and marine spatial planning to delineate and safeguard these areas from conflicting activities. Continued monitoring of reef conditions and environmental education involving local organizations are also crucial. Improving conditions for cultivating massive coral species and establishing genetic banks across nursery sites are essential. Furthermore, advancing assisted reproduction strategies through enhanced understanding of local species' sexual reproduction and adaptation to warming events via metagenomics and stable isotopes studies is imperative. Genetic analyses should be conducted to identify resilient genotypes for propagation. Educational outreach should be enhanced, integrating coral restoration efforts into local tourism and educational programs to foster community involvement and support. Additionally, further research into coral diseases, particularly in the Eastern Tropical Pacific where studies are limited, remains a priority.

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