

RESPITE COVID

SET-BACKS AND SURPRISES

Effects of the COVID-19 lockdowns on the management of coral restoration projects

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Coral restoration initiatives are gaining significant momentum in a global effort to enhance the recovery of degraded coral reefs. However, the implementation and upkeep of coral nurseries are particularly demanding, so that unforeseen breaks in maintenance operations might jeopardize well-established projects. In the last 2 years, the COVID-19 pandemic has resulted in a temporary yet prolonged abandonment of several coral gardening infrastructures worldwide, including remote localities. Here we provide a first assessment of the potential impacts of monitoring and maintenance breakdown in a suite of coral restoration projects (based on floating rope nurseries) in Colombia, Seychelles, and Maldives. Our study comprises nine nurseries from six locations, hosting a total of 3,554 fragments belonging to three coral genera, that were left unsupervised for a period spanning from 29 to 61 weeks. Floating nursery structures experienced various levels of damage, and total fragment survival spanned from 40 to 95% among projects, with *Pocillopora* showing the highest survival rate in all locations present. Overall, our study shows that, under certain conditions, abandoned coral nurseries can remain functional for several months without suffering critical failure from biofouling and hydrodynamism. Still, even where gardening infrastructures were only marginally affected, the unavoidable interruptions in data collection have slowed down ongoing project progress, diminishing previous investments and reducing future funding opportunities. These results highlight the need to increase the resilience and self-sufficiency of coral restoration projects, so that the next global lockdown will not further shrink the increasing efforts to prevent coral reefs from disappearing.

Key words: *Acropora*, Caribbean, coral reef, floating rope nursery, Indian Ocean, pandemic, *Pocillopora*

Implications for Practice

- Regular, ideally monthly, monitoring and maintenance are key components of “coral gardening,” and necessary resources (e.g. emergency funds, additional or local workforce, and redundancy in fundamental structural components) should be allocated to prepare against unexpected events.
- Ensuring sufficient/redundant buoyancy for floating rope nurseries and a long-lasting life span of structures and materials are key factors to ensure coral survival over several months in the absence of maintenance.
- Coral restoration managers should account for frequent, unforeseen schedule breakdowns in their planning. The timely adoption of effective contingency plans ensuring a rapid and effective response to critical situations is a necessary step toward the development of more effective restoration projects less vulnerable to failure and hence capable to attract more funds.

Introduction

Besides their fundamental contribution to biodiversity (Fisher et al. 2015; Strona et al. 2021), coral reefs provide countless

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ecosystem services (Spalding et al. 2017), supplying hundreds of millions of people with food, income and natural resources, as well as contributing significantly to exports and tourism revenues (Costanza et al. 2014). However, coral ecosystems are now experiencing an unprecedented decline due to climate change and other anthropogenic stressors (Hoegh-Guldberg et al. 2017; Hughes et al. 2017a, 2017b), with current coral reefs covering only 50% of their historic extent (De'ath et al. 2012; IPBES 2019). In an attempt to alleviate this critical situation, coral restoration initiatives, based on the general concept of “assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (SER 2004), are flourishing worldwide (Boström-Einarsson et al. 2020).

The exploration of coral restoration strategies dates to the 70s, when the first artificial reefs were established, and self-contained experiments (e.g. transplantation by Maragos 1974) were performed. Today, the field can count on numerous, advanced techniques (e.g. asexual propagation, sexual propagation and substrate enhancement methods; see Boström-Einarsson et al. 2020) that permit to plan coral restoration actions at the local, regional, or global scale (Omori 2019; Boström-Einarsson et al. 2020). The goals of coral restoration projects might extend far beyond the intended ecological scope of increasing coral cover and include socio-economic objectives such as creating environmental awareness and job opportunities for communities (SMART objectives, see Shaver et al. 2020). The project goals determine the technical expertise required for the practical implementation (which might go from the simple use of opportunistic or asexually propagated fragments to that of selective breeding of enhanced corals), as well as the monitoring and maintenance strategies that also depend on the underlying scientific objectives. In turn, these aspects define the cost effectiveness and scalability of a project (Hein et al. 2021).

Currently, about half of all restoration projects use the cost-effective, two-step “coral gardening approach” (Bayraktarov et al. 2019; Boström-Einarsson et al. 2020). In coral gardening, coral fragments are typically first reared under favorable growing conditions (i.e. an optimal combination of exposure to light, sedimentation, water flow, temperature etc.) in artificial in-situ or ex-situ structures before they are transplanted to the target (degraded) restoration site (Rinkevich 1995, 2000; Epstein et al. 2001). Among the different potential in-situ nursery structures apt to the task, which include, among the others, tables, frames, or trees, mid-water floating nurseries have proven very efficient, permitting to rear thousands of asexually produced fragments at low costs (Shaish et al. 2008; Levy et al. 2010). For this, they are commonly used in a large number of projects and localities such as in the Red Sea (Shafir et al. 2006), Philippines (Shaish et al. 2008), Tanzania (Mbije et al. 2010), Seychelles (Frias-Torres et al. 2015), the Arabian Gulf (Nithyanandan et al. 2018), and Latin America (Bayraktarov et al. 2019).

Regular monitoring and structure maintenance during the coral nursery phase (typically monthly) play a critical role for a project's success (Shafir et al. 2006; Frias-Torres et al. 2018). Monitoring consists of data collection on stock rearing performance, primarily represented by growth rate and survivorship, and structure inspections. Maintenance includes repairs, manual cleaning of the nurseries to protect growing corals from biofouling, competition, and

corallivorous organisms (e.g. Levy et al. 2010; Shafir & Rinkevich 2010, Frias-Torres et al. 2018). These tasks, and particularly the need for continuous maintenance, can be very labor-intensive, with the effort varying from hundreds to thousands of person-hours, depending on nursery type, project scale, and objectives (e.g. Shaish et al. 2008; Mbije et al. 2010). Hence, the availability of supporting workforce has been identified as the main challenge for the coral gardening method (Hein et al. 2021), with many successful projects relying on volunteering or citizen science initiatives, or on the collaboration with tourism entities (Hesley et al. 2017).

Unpredictable and unexpected global events can generate additional challenges and even trigger critical failures in otherwise solid and effective restoration projects. The novel SARS-COV-2 (the disease caused by Severe Acute Respiratory Syndrome Coronavirus 2 and labeled COVID-19), originally reported in 2019, was declared a pandemic by the World Health Organization in early 2020. The pandemic has impacted almost every aspect of human society (El Keshky et al. 2020), including the field of research and conservation management, for example, by reducing the availability of educational and research opportunities (Rashid & Yadav 2020; Pokhrel & Chhetri 2021), delaying supply chains (Guan et al. 2020), reducing planning security, and restricting movement. In an attempt to control rising infection rates, governments enforced border closures, travel restrictions, and strict lockdowns in all major countries, a needed measure with numerous side effects. For example, conservation activities that rely on tourism flow and public engagement were severely affected, as documented for US national parks (Miller-Rushing et al. 2021).

Although the discipline of coral restoration has witnessed some setbacks in its young history, often related to natural events such as tsunamis and hurricanes (Symons et al. 2006; Hernández-Delgado et al. 2014), the current practical challenges are unprecedented. The pandemic has affected efforts and activities around the globe, often impacting funding, interrupting supplies, and immobilizing workforce. Recent research in the Tropical Western Atlantic showed that the disruptions to coral restoration practitioners caused by the COVID-19 pandemic were related to financial uncertainty, lack of reliable workforce, and inability to access field sites, due to government lockdowns and travel/boating restrictions that impeded even local workers to perform regular work (Cheek 2020). This resulted in the abrupt suspension of monitoring and maintenance activities and offers an example of how the pandemic-related containment measures might have substantially impacted coral restoration projects. Two years into the pandemic, it is unclear to what extent COVID-19 will impact restoration efforts worldwide. Shedding light on their current situation emerges as critical to improve restoration projects' resilience and improve preparedness against any future unexpected scenarios.

To this end, here we explore how the COVID-19 pandemic has impacted a representative suite of coral restoration projects (using mid-water rope nurseries for coral gardening) in the Caribbean Sea (Colombia) and in the Indian Ocean (Seychelles and Maldives). In our study areas coral reef ecosystems are not only important from an ecological and biodiversity perspective, they also provide vital support to the local economies, especially

through tourism. The Caribbean and Indo-Pacific are already facing multiple natural and anthropogenic threats such as bleaching events (Pisapia et al. 2019; Cramer et al. 2021), corallivores outbreaks (Saponari et al. 2018), and diseases (Montano et al. 2012, 2016; Estrada-Saldívar et al. 2020) that have caused repeated mass mortality events and an extensive loss of coral cover, and therefore require active intervention, including coral restoration as a potential effective form of mitigation.

In Colombia, a collaboration between the provincial environmental authority and regional NGOs resulted in the adoption of the large-scale mid-water floating rope nursery system developed in Seychelles to substantially upscale Colombia's restoration efforts (Bayraktarov et al. 2020). In the Seychelles, coral restoration efforts started already in 2010, after various mass bleaching events and tsunamis had negatively impacted coral reefs. Between 2012 and 2014, the Reef Rescuers Project of Nature Seychelles successfully employed mid-water rope nurseries to grow over 45,000 corals (Montoya-Maya et al. 2016). To upscale restoration practices in the Maldives, mid-water nurseries have been successfully installed over the last few years in several resorts, including

Athuruga island, as well as on the local island of Magoodhoo (Dehnert et al. 2021). Here, we report and discuss qualitative and quantitative data assessing the effects of lack of monitoring & management in four coral restoration projects in Colombia, Seychelles, and Maldives following COVID-19-related travel restrictions, and countrywide multiple lockdowns leading to the absence of available workforce in all cases. In doing that, we discuss various general aspects related to the broader implications of the monitoring and managing break down, and we propose potential practical solutions and recommendations to reduce the potential impact of similar events in the future.

Methods

We assessed the impacts of a mandatory and abrupt halt in maintenance and monitoring on four coral restoration projects located in Colombia (one project with two nurseries), Seychelles (one project with one nursery) and Maldives (two projects with two and four nurseries) (Fig. 1). We collected data from a total of nine floating rope nurseries of 1–5 years old, ongoing

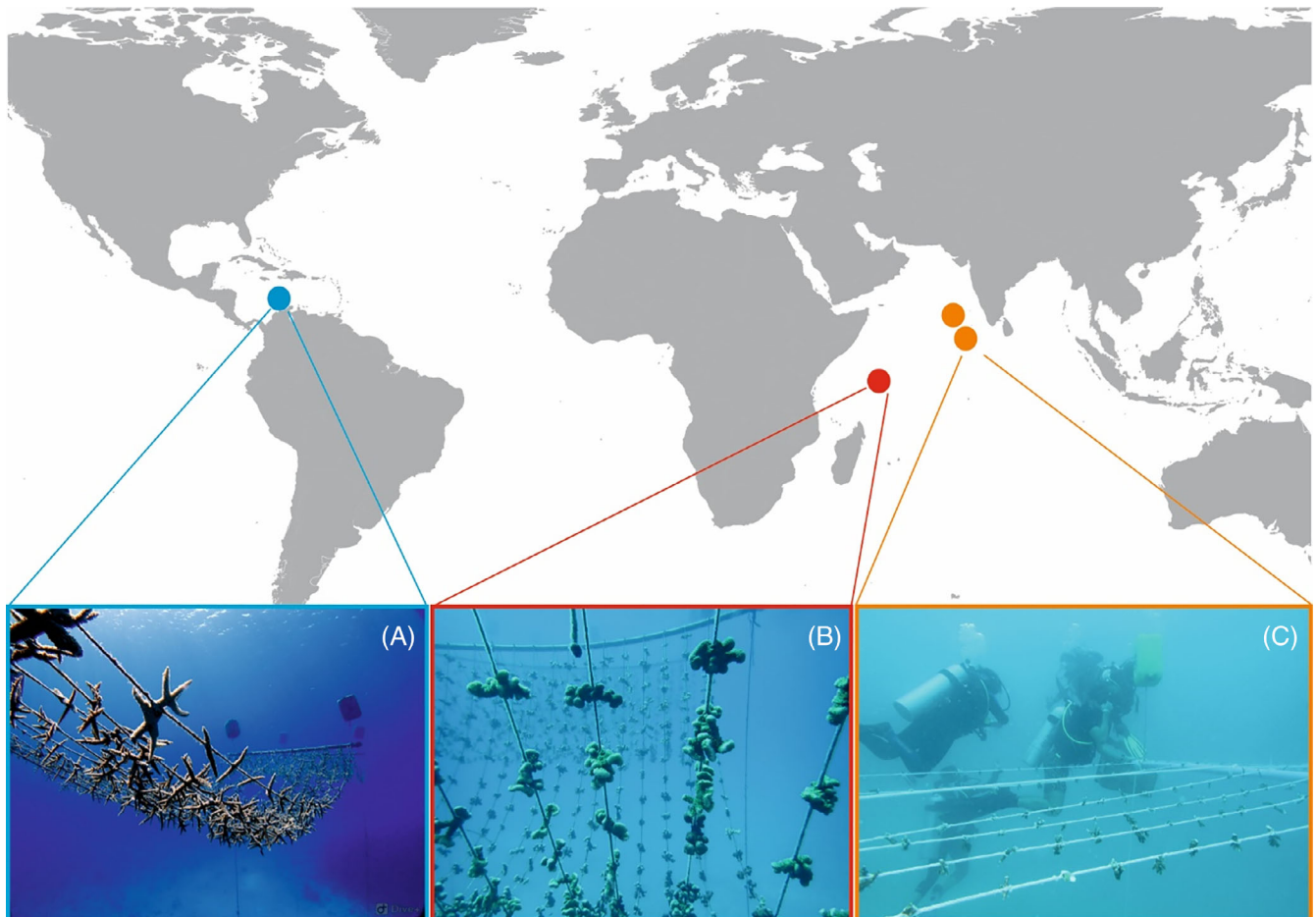


Figure 1. Map of the study area where the projects are located; (A) Providencia Island in Colombia; (B) Seychelles; (C) Maldives. In Colombia, the two nurseries were installed in the same nursery site, 200 m from the coastline of Providencia Island, inside the reef lagoon ($13^{\circ}20'3.20''\text{N}$ $81^{\circ}21'28.09''\text{W}$). In the Seychelles, the nursery was placed ca. 600 m offshore, NW from Cousin Island ($4^{\circ}19'34''\text{S}$ $55^{\circ}39'26.1''\text{E}$). In the Maldives, on Athuruga resort island ($3^{\circ}53'14''\text{N}$ $72^{\circ}48'59''\text{E}$) one nursery was placed in the lagoon, about 350 m away from the shore and one on the house reef, 50 m from the shore. On Magoodhoo local island ($3^{\circ}04'45''\text{N}$ $72^{\circ}57'53''\text{E}$) four nurseries were placed in the lagoon, approximately 200 m away from the shore.

Table 1. Comparison of floating rope nursery projects in Colombia, Seychelles, and the Maldives and the impact of forced monitoring and maintenance interruption resulting from the COVID-19 pandemic.

Location	No. of Nurseries (Build in)	Coral Nursing Environment	Monitoring and Maintenance	Interruption Time	No. of Fragments	Genera/Species	Fragment Survival	Nursery Condition	Main Issues	Project Implication
Colombia—Providencia	1 (2018)	6 m deep lagoon; sandy bottom; current: slight; temp. range: 28–30°C	Monthly; one research staff, one technician, and four trained fisher folks; ca. 20 person-hours/month	30 weeks	1,500	<i>Acropora palmata</i>	60%	Partially collapsed	Lack of buoyancy, macroalgae overgrowth	Considerable coral loss, structure repair
Colombia—Providencia	1 (2018)	6 m deep lagoon; sandy bottom; current: mild; temp. range: 28–30°C	Monthly; one research staff, one technician, and four trained fisher folks; ca. 20 person-hours/month	30 weeks	200	<i>Acropora cervicornis</i>	40%	Fully collapsed	Lack of buoyancy, macroalgae overgrowth	Major coral loss, difficult repair
Seychelles	1 (2018)	Sandy bottom at 17 m, exposed to NW wind trade; current medium during SE wind trade; temp. range: 26–31°C	Monthly; three technical staff; two to four volunteers; ca. 10 person-hours/month	46 weeks	192	<i>Pocillopora</i> spp.	75%	Partially collapsed	Lack of buoyancy; weight of fragments	Minor coral loss after structure repair
Maldives—Athuruga Resort Island—Lagoon	1 (2018)	15 m deep lagoon; sandy bottom; current: no; temp. range: 28–30°C;	Monthly; two resort staff; ca. 10 person-hours/month	29 weeks	346	83 <i>Acropora</i> , 190 <i>Pocillopora</i> , 73 <i>Porites</i>	94.5%	Partially collapsed	Lack of buoyancy; macroalgae overgrowth, disease	Minor coral loss after structure repair
Maldives—Athuruga Resort Island—Reef	1 (2020)	20 m deep inshore reef; rubble and sandy bottom; current: intermediate; temp. range: 28–30°C;	Monthly; two resort staff; ca. 16 person-hours/month	29 weeks	770	301 <i>Acropora</i> , 469 <i>Pocillopora</i>	80.4% (46% new stock; 94% older stock)	Fully functioning	Macroalgae overgrowth	Minor (partial loss of young fragments)
Maldives—Magodhoo Local Island	4 (2017)	15 m deep lagoon; sandy bottom; current: slight; temp. range: 28–30°C	Monthly; two research staff; ca. 20 person-hours/month	61 weeks	846	715 <i>Acropora</i> , 114 <i>Pocillopora</i> , 17 <i>Porites</i>	Approximately 80%	Fully collapsed	Lack of buoyancy; weight of fragments	Considerable loss of data, corals and difficult repair

restoration projects (Table 1). Although these nurseries slightly differ in dimensions and holding capacities, they all follow the design by Levy et al. (2010) and Edwards et al. (2010). Briefly, the floating rope nursery consists of 3–5 high-pressure PVC

pipes (HP PVC) placed approximately 5 m apart, each with 10–20 m-long coral holding ropes (4–5 mm braided nylon) perpendicularly attached with anti-slip knots (Frias-Torres et al. 2018). The nurseries are attached to the deep sandy seabed

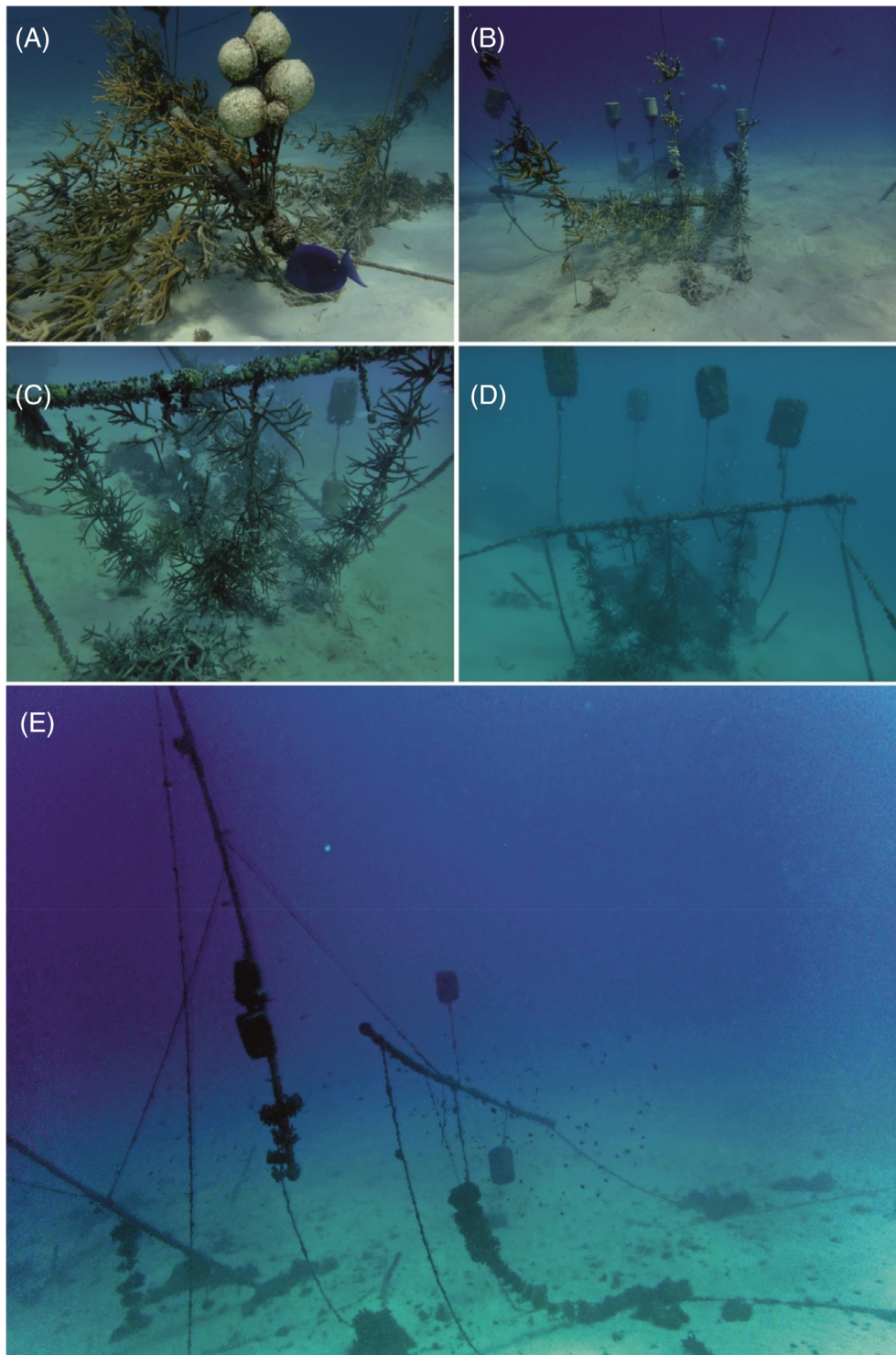


Figure 2. Panel showing similar collapsing patterns between the three different locations; (A and B) Providencia Island, Colombia; (C and D) Magoodhoo Island, Maldives; (E) Seychelles.

by anchor lines (10 mm braided nylon) tied to 1.5–1.6-m-long angle bars hammered halfway into the seabed and maintained at a depth of 4–6 m below the sea surface by using recycled 18-L plastic jerrycans or buoys (Frias-Torres et al. 2018).

In Colombia (Fig. 1A), data were collected from two floating rope nurseries that were installed in 2018: one nursery with a total of 1,500 five-centimeter fragments of *Acropora palmata* and one nursery with approximately 200 ten-centimeter fragments of *A. cervicornis*. Both structures are part of the same nursery site, which is located southeast of Providencia Island inside the reef lagoon, about 200 m from the coast, each nursery running parallel to the coastline and separated by 5 m of open sand. In contrast to nurseries in the Maldives and the Seychelles, both jerrycans and 20-cm polystyrene buoys were used to float the nursery. Monitoring and maintenance comprised monthly data collection on fragment health, removal of algae and biofouling with toothbrushes from coral ropes and PVC pipes, buoyancy adjustments (i.e. addition and replacement of jerry cans or polystyrene buoys), and anchoring reinforcing (i.e. hammering of angle bars). Anchor ropes were replaced annually, with last change conducted in October 2019. Monitoring and maintenance were conducted by park rangers and local fisher folks previously trained in coral gardening and supervised by research staff from project organizations. Both nurseries experienced a no-attendance period of 30 weeks (210 days) after the last monthly monitoring session in February 2020. No last-minute preparations were conducted prior to the start of the pandemic lockdown in March 2020.

In the Seychelles (Fig. 1B), data relate to a single floating rope nursery (fully refurbished in 2018) stocked with 192 fragments of the genus *Pocillopora*. Monthly monitoring and maintenance, including cleaning of ropes, PVC, jerrycans, and anchors, was performed by the staff employed at Nature Seychelles. The lockdown and COVID-19-related restrictions caused the limitation in the workforce and no actions could be taken prior the no-monitoring and maintenance period. The nursery was left unattended for a total of 46 weeks (325 days) after the last monthly monitoring session in May 2020.

In the Maldives, data from two locations (Athuruga and Magoodhoo island) in two different atolls were collected

(Fig. 1C). On Athuruga Resort Island in South Ari Atoll, two floating rope nurseries constructed in the lagoon (in 2018) and in the house reef (in 2020) were filled with 346 fragments (83 *Acropora*, 190 *Pocillopora*, and 73 *Porites*) and 770 fragments (301 *Acropora* and 469 *Pocillopora*), respectively. In the reef nursery, 214 of these fragments (198 *Acropora* and 16 *Pocillopora*) were stocked just 1 month before shutdown, still showing healing fragment wounds, hereafter referred to as “new stock,” while all other, “older stock,” were at least farmed for 2 months. Monthly monitoring, including data collection on fragment health and growth, and structure cleaning and repairs as described above, was conducted by the resort’s marine biologists until the nurseries had to be abandoned on short notice in April 2020 for a period of about 29 weeks (200 days). Just before the resort closure, some last-minute preparations, including cleaning coral ropes, cleaning and topping up air filled jerrycans, and adding redundant jerrycans for additional structure support, were conducted in the house reef nursery, while no actions could be taken to prepare the lagoon nursery to a period of non-monitoring and maintenance.

On the second Maldivian study site in Faafu Atoll, four mid-water rope nurseries were constructed in the lagoon of Magoodhoo Island in 2017 (Fig. 1C), where the MaRHE center marine field station is located, hosting 846 fragments (84.5% *Acropora*, 13.5% *Pocillopora*, and 2% *Porites*). They were monitored monthly following the same monitoring protocol applied on Athuruga by the center’s research staff till February 2020 and then abandoned without further preparations for 61 weeks (425 days) due to travel restrictions.

On return to study sites in Colombia, Seychelles, and the Maldives, a qualitative assessment of the general state and quality of structures was performed. In addition, a quantitative assessment of fragment condition (categorical: “alive,” “partially alive,” or “dead”) was conducted using direct counts where possible or estimated when nursery conditions did not allow for accurate counts.

Results

After a 29–61-week period of unplanned no-maintenance, eight of the nine assessed nurseries were partially or fully collapsed,

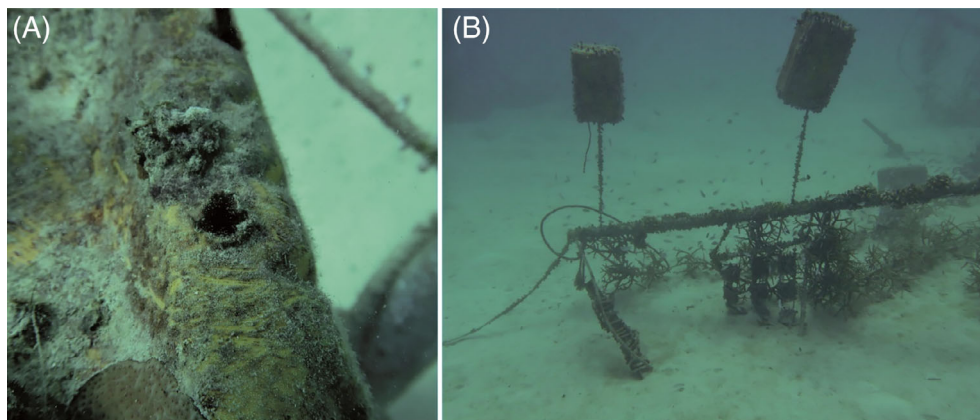


Figure 3. (A) Close-up of a punctured jerry can. (B) A collapsed floating rope nursery located in Magoodhoo Island (Maldives).

with fragment survivorship ranging from 40% to more than 90% (Table 1).

In Colombia, the two nurseries were found partially (i.e. some structure elements retaining positive buoyancy) and fully (i.e. all elements on the seafloor) collapsed after 30 weeks. We recorded a survival rate of approximately 60% for the gardened colonies of *A. palmata* in the partially collapsed nursery and 40% for those of *A. cervicornis* in the fully collapsed nursery. Since no sign of diseases or predation was observed, the mortality was mainly attributed to macroalgae overgrowth and sand abrasion,

as a result of the nursery structures sinking to the bottom. The collapse was partially due to the lack of buoyant force from lost or punctured jerry-cans or collapsed buoys (4/10) combined with the increased weight of coral fragments. Most of the ropes got entangled with each other and adjacent corals fused, complicating the assessment and rescue of healthy coral colonies (Fig. 2). The growth of additional corals, in this case hydrocorals of the genus *Millepora*, was extensively observed on the PVC pipes of both nurseries. Although both nurseries were structurally repaired, complete removal of hydrocorals was nearly

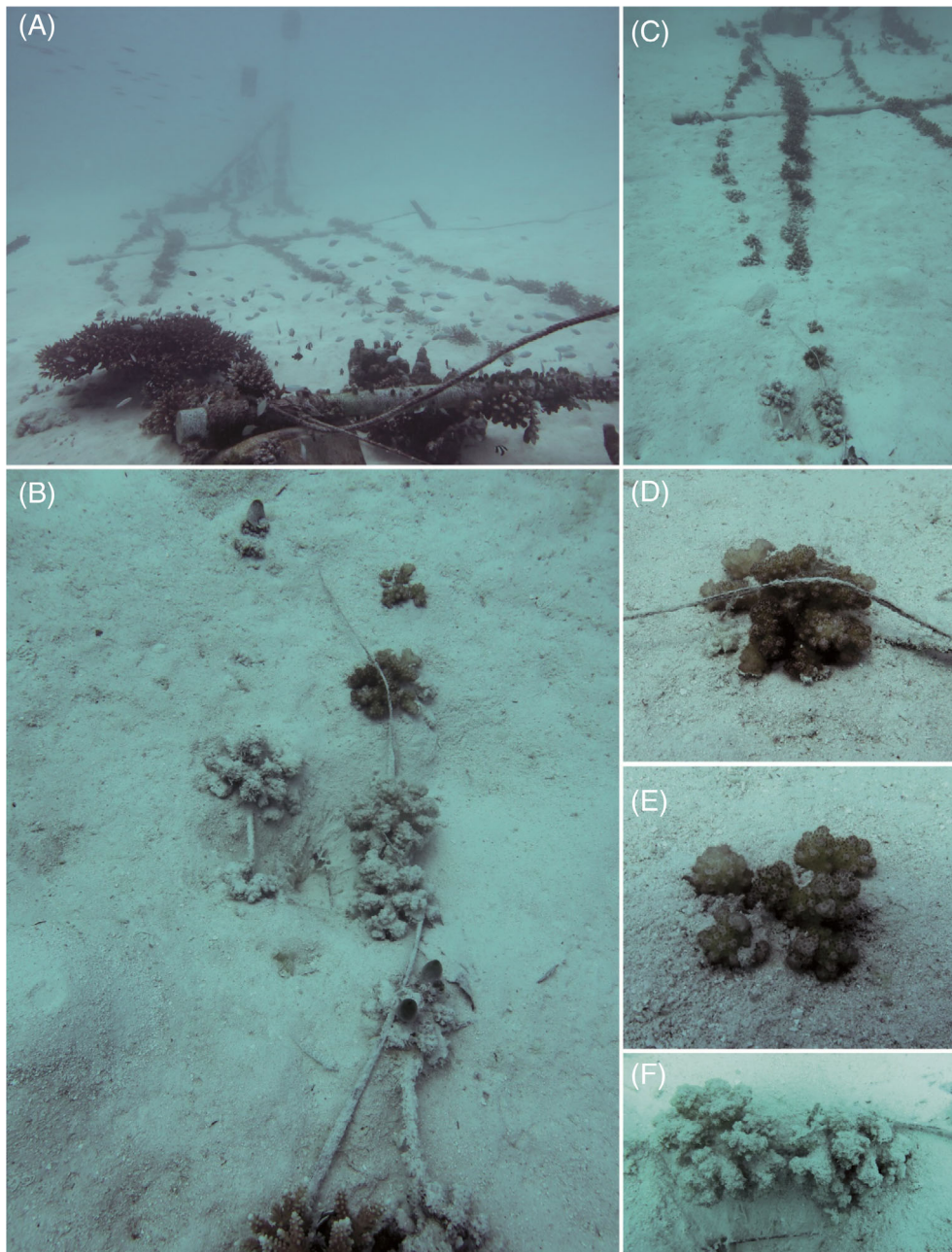


Figure 4. (A–C) Overview of a collapsed floating rope nursery in Magoodhoo Island with ropes and colonies laid on the bottom; (D,E) fragments of *Pocillopora* partially covered by sand; (F) recently dead colonies of *Pocillopora*.

impossible. While ropes with surviving *A. palmata* colonies were placed back in the nursery, all surviving *A. cervicornis* colonies were outplanted to a nearby reef.

In the Seychelles, the nursery abandoned for 46 weeks also partially collapsed. Although six of the 12 jerrycans were punctured, we found that structural damages were mainly attributed to the corals' increased weight that caused the partial collapse of the structure. This resulted in the loss of those colonies that remained on the sandy bottom for a long period of time (see Table 1). Overall, the structure experienced significant damage with approximately 25% of the fragments showed signs of suspected diseases and were removed.

In the Maldives, on the island of Athuruga, the two nurseries were abandoned for 29 weeks during the wet South-West monsoon season, characterized by enduring storms and rough sea

conditions. On return, the reef nursery was found in a good condition. All anchors were still in place and none of the ropes were damaged or entangled. Although two out of the 12 jerrycans were found punctured and another one was missing, the structure's buoyancy was still granted by the additional jerrycans. The recorded overall fragment survival was high (80.4%), even though fragments from the new stock, that had been farmed for only 1 month before the forced abandonment, suffered a much higher mortality (54.2%, all *Acropora* fragments) than the older stock (6.3%, 31 *Acropora* and 8 *Pocillopora* fragments). Most *Acropora* fragments from the new stock died due to biofouling.

In contrast, Athuruga's lagoon nursery suffered a partial structure collapse (Table S1). Of the eight jerrycans attached to the PVC frame (tree per outer pipes and two on middle pipe), the two supporting the middle part of the nursery frame deflated. Two of the six coral ropes and two of the four tension lines tore

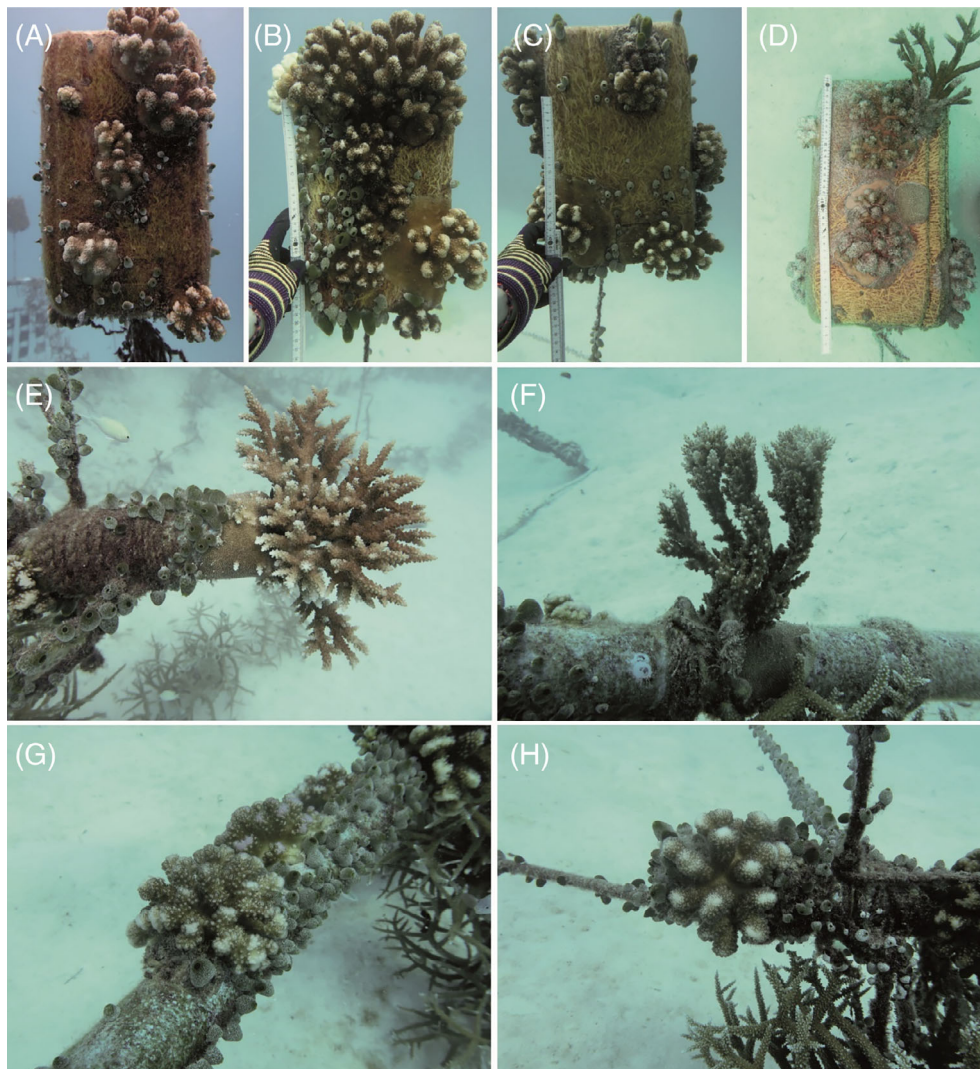


Figure 5. Images showing coral colonies overgrowing PVC pipes and jerry cans in Magoodhoo Island; (A–D) Jerrycans fully covered by *Pocillopora* colonies over 15 cm in diameter; (E and F) *Acropora* spp. colonies unexpectedly overgrowing PVC pipes; (G and H) examples of *Pocillopora* colonies growing on PVC pipe and entangled ropes, respectively.

in several places (all 2 years old 5 mm nylon) (Fig. S1). Despite the partial collapse, fragment survival was high (94.5%; dead fragments: 15 *Acropora*, 1 *Pocillopora*, 3 *Porites*) as most coral ropes were supported by the outer frame structure and did not reach the bottom. Only 20 fragments that sank to the sandy lagoon floor at 15 m suffered partial mortality (5.8%; 5 *Pocillopora* and 15 *Porites* fragments). The survival of *Pocillopora* fragments (99.5%, $n = 190$) was higher than the *Acropora* fragments (81.9%, $n = 83$), which were impacted by algae overgrowth and possibly disease. Following the assessment, all necessary structural repairs were conducted, damaged fragments were removed or restocked and monitoring was continued.

Compared to Athuruga, more damage was observed on the four mid-water rope nurseries located in Magoodhoo. All of them were found fully collapsed, with structural elements twisted and entangled, after over a year (61 weeks) of unplanned non-monitoring and maintenance. While we identified in the punctured and deflated jerrycans (Fig. 3A) the main cause of nurseries' structural collapse, it is reasonable to assume that, at least in some cases, the weight of older fragments might have played a significant role (Figs. 3B & 4A–C).

Following the nurseries' collapse, approximately 20% of coral colonies spent a considerable time lying on the bottom, and some of the colonies were completely covered by sand. As a result, approximately 5% of fragments suffered partial mortality, while approximately 15% suffered total mortality (Fig. 4D–F). Conversely, approximately 80% of colonies survived as entanglement and overlapping of colonies prevented direct contact with the seafloor. As observed in Colombia, most of the ropes were entangled with other ropes, coral colonies, PVC pipes, and jerrycans, in some cases indicating a twist of the entire structure. Consequently, some coral colonies grew over adjacent ropes, or fused with fragments of the same genotype on neighboring ropes, limiting the precise counts of survival. Mortality was almost exclusively due to suffocation by sediment, while we detected no signs of algal overgrowth, bleaching, predation and diseases. Additionally, many jerrycans and PVC pipes were found to be fully covered by *Pocillopora* colonies of an average size of over 15 cm in diameters (Fig. 5). Extensive repairs and ad-hoc out-planting of larger colonies followed the damage assessment.

Discussion

Here we explored the question of whether and to what extent the interruption of monitoring and maintenance activities due to global mobility restrictions as a result of the COVID-19 pandemic has impacted ongoing coral restoration projects. The pandemic has affected conservation activities, including coral restoration projects, in various ways, by halting practical operational activities, reducing available workforce, and delaying management planning (Cheek 2020; Corlett et al. 2020; Miller-Rushing et al. 2021). In this context, we found that COVID-19-related restrictions on maintenance to coral nursery infrastructure resulted in significant loss of farmed corals with further negative implications for project progress. Therefore, this unfortunate situation forces us to consider the possibility that similar scenarios might materialize again in the future and

hence calls to improve our preparedness. Identifying critical vulnerabilities and developing protocols to prevent future, unexpected maintenance breakdowns or, at least, mitigate the resulting impacts emerges as a novel priority in coral restoration. In this study, we have made the first steps in this important direction, by assessing how multiple coral reef restoration projects that were initiated before the onset of the COVID-19 pandemic have responded to prolonged abandonment enforced by global mobility restrictions. As the pandemic was almost instantaneous, the research had not been planned beforehand. Consequently, we had to take the most information possible from the available data, and our resulting assessment is a qualitative-quantitative one. We have focused on different aspects quantifying the resilience of coral nurseries to abandonment, namely structural performance and coral survivorship, paired to considerations on the effects of restrictions on project management. The considered projects are informative in that: (1) They are representative of different environmental settings being located in three distinct biogeographic provinces in two oceans (see Spalding et al. 2007) but are still comparable as: (2) They make use of a consistent restoration approach, “coral gardening” through floating rope nurseries; (3) They have similar size in terms of number of reared colonies; and (4) They make use of one common coral growth form (i. e. branching) and at least one common genera (i.e., *Acropora*). Moreover, the coral gardening approach, because cost-effective, is also currently one of the most applied techniques practiced by coral restoration projects around the world (Bayraktarov et al. 2020; Boström-Einarsson et al. 2020), which makes our conclusions widely applicable and of interest to a wide audience.

Our observations from Colombia, Seychelles, and Maldives highlight that buoyancy and material life span are fundamental in ensuring structural longevity for floating rope nurseries since, at all three locations, most of damages to the coral nurseries were due to the consequences of the loss of buoyancy. Specifically, the buoyancy of the nurseries was compromised not only by failures in the materials (e.g. loss of floating devices), but also as a consequence of excessive weight of the reared coral colonies. This emphasizes the importance of preemptively setting up redundant floating devices as both a backup and an enhancement to the necessary ones, as also proven by the case of Athuruga house reef nursery, where the effects of abandonment were mitigated and minimized due to the timely adoption of similar preemptive measures. Some of the failures detected in our study case are likely due to the common adoption of relatively cheap and/or recycled materials in the construction of nurseries. Although it can increase cost, a starting investment in more robust flotation devices with a longer life span and requiring less maintenance, such as “plastic” nautical buoys, could be rewarding in the long term. More in general, investing in the targeted development of reliable and efficient (and possibly plastic-free) flotation devices, as well as of new materials for tension ropes and the other nurseries' structural components, could not only benefit coral restoration, but also lead to technological innovations applicable to other fields.

As this study is limited to floating rope nurseries, the key inferences and recommendations may not be the same for the whole set of methodologies utilized for coral gardening

including trees, tables, spiders, etc. and do not fully represent the operational modifications that these programs will make in the future. Therefore, an analysis of impacts on other techniques and programs worldwide would be required to identify key risks and recommendations across the whole spectrum of coral restoration approaches.

Our assessment indicates that coral restoration projects might suffer substantial damages after less than 1 year with no maintenance. In our study, different coral genera responded differently to the abandonment, with *Pocillopora* fragments (especially those stocked at least 1 month before the suspension of maintenance) having the better rate of survivorship on Athuruga (Maldives), where direct comparison was possible. When Acroporid corals suffered substantial mortality (e.g. Colombia), most of it was due to a combination of sedimentation caused by the collapse of the rope nurseries onto sandy bottoms and algal overgrowth. While impacts from the algal overgrowth stress the need for cleaning efforts in nurseries (Levy et al. 2010; Shafir et al. 2010, Frias-Torres et al. 2018), direct comparison between the Maldivian projects suggests that the degree of cleaning effort needed could vary on a per-case basis. For instance, the low presence of algae observed in Magoodhoo 61 weeks after the last maintenance activity highlights how the choice of an optimal site (in ecological and environmental terms) can significantly reduce the need for active maintenance.

Furthermore, the colonization of jerrycans and PVC pipes by new coral recruits of different species observed in Magoodhoo and Colombia, with some of the colonizers being unexpected and locally rare to Magoodhoo, emphasizes the idea that coral nurseries might act as floating ecosystems (Shafir & Rinkevich 2010) offering further arguments supporting the importance of restoration actions (Hein et al. 2021).

While colony mortality and nursery structure failures can be mitigated and minimized during periods of forced site absence, monitoring of projects involving data collection, analysis, and evaluation of nursery and outplant sites cannot continue without the necessary in-situ workforce. As the projects discussed here demonstrate, the global work force immobility made it often impossible for organizations, including NGOs, universities, and touristic resorts, to retain international workers or volunteers on site. Continuity in monitoring and data collection activities is a critical element in restoration project, possibly reducing the likelihood for success even during “normal” circumstances (Hein et al. 2019; Boström-Einarsson et al. 2020; Shaver et al. 2020). Such criticality has now been made apparent by the COVID-19 pandemic. Interruptions in data collection and analysis, as experienced by all three case studies, can also undermine the confidence of stakeholders and funders in restoration actions, generating a dangerous loop where the cost of securing projects against failure cannot be covered, and the subsequent failures compromise further funding acquisition.

In conclusion, this study provides evidence that floating nursery structures, in the investigated areas, can endure several months of abandonment with little preparation, if necessary, as long as sufficient buoyancy is ensured. However, disruption of monitoring and data collection can cause a cascade of events, resulting in potential financial and planning uncertainty, which

can ultimately jeopardize overall longevity, performance, and success of these projects. Management strategies should start with the preparation of contingency plans focusing also on workforce sources. In particular, project budgets should prioritize the involvement of local workforce to minimize the potential impact of restrictions in mobility. This might be a win-win strategy bringing also substantial benefit to local economies. The current pandemic not only continuously forces researchers and conservationists to adapt their *modus operandi*, but also highlights our society's fragility and dependence on resilient and healthy ecosystems, for which coral restoration projects around the world make every effort.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Mid-water floating nurseries structure on Athuruga, Maldives after 29 weeks of non-maintenance. A-B) structures in very good condition and fully functional; C-D) examples of presence of major damages compromising functionality; E-I) example of structures showing signs of damages, but maintaining close to full functionality.

Table S1. Mid-water floating nurseries structure assessment on Athuruga, Maldives, after 29 weeks of non-maintenance.

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