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Article

Active Coral Restoration to Preserve the Biodiversity of a Highly Impacted Reef

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Abstract: Maldivian coral reefs have been experiencing significant degradation due to a combination of global climate change and local anthropogenic pressures. To enforce the conservation of coral reefs worldwide, coral restoration is becoming a popular tool to restore ecosystems actively. In the Maldives, restoration interventions are performed only around touristic islands, where there are economic resources available to support these projects. Unfortunately, on local islands, coral restoration does not benefit from the same support and is rarely boosted. A challenging coral restoration intervention has been performed, for the first time, a on a local island of the Maldives affected by intense human pressures that caused the degradation of its reefs. A total of 242 coral fragments were collected from impacted colonies and transferred to the coral nursery of the island. Survival and growth rates of the fragments were monitored for 12 months. After one year, a survival rate of 70.2% was recorded. Although this rate might appear lower when compared to other restoration experiences, it is very promising considering the origin of the fragments and the poor quality of the environment where they have been transplanted. Some potential threats to the success of this restoration have also been identified, i.e., water temperature anomaly, diseases and parasites, the latter being the leading causes of coral mortality. The procedure presented here is comparatively less expensive than the typical relocation of entire coral colonies from donor healthy reefs to degraded reefs, thus providing an opportunity and a viable option also for local islands to restore their reefs and preserve local biodiversity.

Keywords: marine ecosystem restoration; habitat restoration; artificial reef; restoration strategies; biodiversity conservation

1. Introduction

Coral reefs are considered one of the most biodiverse and productive ecosystems on Earth [1,2]. Referred to as the rainforests of the sea, they host 25% of the total marine biodiversity, even though they cover only 0.2% of the seafloor [3]. Coral reefs provide a wide variety of ecosystem services: they provide nursery and aggregation areas for marine life [4,5], they protect coasts, support fishery and tourism [6–8], create local identity and provide cultural connections [6,9]. Despite their incredible value, coral reefs are fragile ecosystems and in the past decades they have been declining worldwide due to a combination of global and local anthropogenic pressures [10,11]. Unfortunately, the synergic effect of global and local impacts is eroding reef resilience [12], making natural recovery slower or even unreachable [13].

The United Nations has recently launched the UN Decade on Ecosystem Restoration, which aims to promote global cooperation for the restoration of degraded ecosystems. From 2021 until 2030, the United Nations are asked to implement projects that combat climate change, preserve and restore biodiversity, and safeguard food and water supplies [14]. Ecological restoration seeks to initiate or accelerate ecosystem recovery following damage [15]. This practice is not a substitute for environmental conservation, but simply aims to assist in the recovery of degraded ecosystems.

Coral reefs are considered priority ecosystems for environmental restoration interventions, which can be broadly categorised into passive or active practices [16]. Both passive and active approaches to coral restoration are crucial components of a conservation strategy that seeks to optimise biodiversity conservation and ecosystem services provision [17]. Passive coral restoration focuses mainly on habitat maintenance and management, allowing natural processes to mitigate impacts with minimal to no human interference [18]. Due to the high intensity and frequency of human pressures on coral reefs, passive conservation is no longer enough [16], and severely degraded reefs, especially those missing breeding populations of formerly abundant organisms, might not be able to recover in a short time [18,19]. Active restoration projects have thus been increasing all around the world [15], providing direct human intervention through coral gardening that can be applied either *in-situ* or *ex-situ* within coral nurseries [20]. The *ex-situ* methods involve the sampling and the transfer of either entire colonies or coral fragments on artificial substrates in a nursery area with controlled environmental conditions. When coral fragments have reached a suitable size, they can be relocated to the degraded reef and then monitored over time [21].

The Maldives is a nation of coral islands built by the low-lying accumulation of unconsolidated sediment formed from the skeletal remains of carbonate-producing reef organisms, mainly corals [22,23]. Healthy coral reefs are thus vital for the existence and the economic sustainability of the Maldives because they improve tourism, provide coastal protection, and sustain the growing population with abundant food [24].

Coral reefs of the Maldives have been largely affected by climate change and global warming [25]. Rising sea level is causing flooding on many islands [26]. Global warming is exacerbating the ENSO phenomenon across the equatorial Pacific Ocean [11], a natural periodic fluctuation in sea surface temperature (known as El Niño) and in air pressure of the overlying atmosphere (known as Southern Oscillation) [27]. Due to the warming in sea surface temperature (SST), intense ENSO episodes are causing more severe, long-lasting and frequent coral bleaching events across the country, with consequent mass coral mortalities [28].

In the past 40 years, coral reefs around the Maldives have also experienced increased local anthropic pressures, such as coastal development and land reclamations [12]. The capital atoll of North Malé is almost entirely developed and the surrounding area of the capital city of Malé (i.e., the Greater Malé Area) is the most populated of the Maldives [29]. This huge human development determined a decline in the water quality [30], challenging even further the surrounding reefs.

Low water quality may increase the spread of coral diseases [31] by reducing coral resistance to microbial infections while increasing pathogen virulence, leaving coral reef ecosystems in a state of disrepair with little hope of recovery [32]. Coral diseases have been identified as one of the most important causes of coral loss and different environmental factors have been correlated to numerous disease processes [33]. Their occurrence is likely to be driven not by a single factor but rather by a multifactorial process that facilitates the emergence of pathogens in vulnerable ecosystems [34]. Although coral diseases have been largely investigated, less is known from the Indo-Pacific area [31]. Stony corals also provide microhabitats for thousands of micro- and macro-parasitic and commensal organisms, which use the tissue and the skeleton of coral colonies as substrate. Currently, there are more than 165,000 described species of coral-associated invertebrates along a spectrum of symbiosis from mutualism to commensalism and parasitism. Parasites may stress the coral and, to some extent, they may cause coral mortality through feeding and boring activities [35,36].

Coral restoration efforts throughout the Maldives are surprisingly few [21]. While luxury resorts operate small-scale restoration activities for tourism purposes [37], there are no examples of active coral restoration programs at the national scale, making it challenging for local islands and NGOs to find funding for these interventions. Transplanting coral colonies from healthy donor reefs to degraded reefs is considered the best approach to benefit recruitment and accelerate recovery [13,19,21]. However, considering the cost of the equipment needed for the intervention, the cost of the coral relocation (including boat fee, fuel, and dive gear rentals), and the cost of monitoring activities, active restoration projects cannot be afforded by most of the local Maldivian communities because of the lack of funding and of local resources. Alternative economically viable initiatives are thus recommended for restoring the degraded reefs of the Maldives.

This study describes a first experiment of small-scale, low-cost, active coral restoration of a degraded reef in the local island of Villimalé (North Malé atoll) subjected to a high level of human pressures. Instead of transplanting entire healthy coral colonies from a donor reef, fragments of corals were harvested directly from the few colonies still alive in the degraded reef of the island, and were transferred to the nearby coral nursery to enhance their growth in a controlled environment, in order to grow adult colonies for restoring and preserving the local biodiversity. During the 1-year monitoring of the survival and the growth rate of coral fragments, the occurrence of coral diseases and parasites has also been monitored.

2. Materials and Methods

2.1. Study area and field activities

The Maldives is an archipelago of 26 natural atolls with approximately 1,200 small, low-lying, coral islands stretching from North to South over an area of 860 km^2 in the Indian Ocean. Coastal and marine ecosystems dominate the environment in the Maldives, as more than 99% of the territory is covered by the ocean [23].

This study was conducted at Villimalé island (4°10′23.79″ N, 73°29′7.29″ E), in the North Malé atoll (Figure 1), between December 2021 and November 2022. Villimalé is the 5th administrative district of the capital city of Malé, and it is part of the Greater Malé Area along with Hulumalé island [38,39]. Villimalé is the last island of the Greater Malé Area and, with its three natural beaches, it is the preferred destination for the local community to spend weekends and holidays. With nearly half of the Maldivian population residing in this area [29], the surrounding waters of Villimalé have high concentrations of organic wastes and chemical pollutants [40]. Additionally, Villimalé is near the garbage island of Thilafushi, used as a dumping area since the early 1970s. The waste on the island has been used to fill the lagoon and reclaim the land, causing further pollution of the surrounding waters [41]. A warning alert for coral bleaching was dispatched in this region for the period between the middle of April and the middle of May 2022, due to increased sea surface temperatures because of the severe heat wave consequent of an ENSO episode [42].

For the restoration intervention, six metal frames were deployed between 1.5-2.1 m depth (depending on the tide) on the North-West corner of Villimalé island, where a coral nursery already exists (Figure 1). The metal structures were designed to match the natural height (about 30 cm) of coral rocks on the reef flat and were double-coated with resins and sand to avoid the spread of rust and create a suitable substrate for the corals.

The reefs around Villimalé are dominated by the corals of the genus *Pocillopora*, which have been highly affected by diseases and parasitism in the last years causing the death of most of the colonies. A total of 242 fragments of *Pocillopora meandrina* (n = 164) and *Pocillopora verrucosa* (n = 78) were collected from the few living corals remaining on the reefs by harvesting healthy branches, were transferred to the coral nursery and attached directly to the frames using cable ties. The first monitoring was carried out two weeks after the transfer of the coral fragments to evaluate their response to mechanical stress, and then the survival and growth rates were monitored monthly for 12 months (from December 2021 to November 2022). To ensure the success of the restoration experiment, scientific divers surveyed the coral nursery three times per week to perform maintenance on the frames. For consistency with the conditions in the donor reefs, neither diseased corals nor parasites were removed, and the maintenance focused on cleaning the frames and ensuring the stability of the fragments on the substrate.

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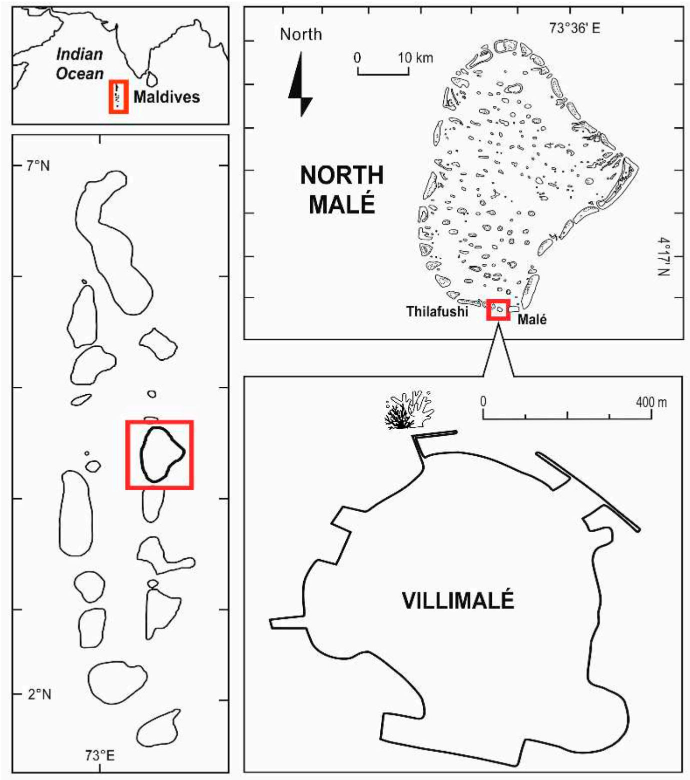

Figure 1. Map of the Maldives with the location of Villimalé Island in the North Malé atoll, close to the capital city of Malé and to the garbage island of Thilafushi. The symbol of the corals shows the location of the nursery area on Villimalé Island, where the restoration experiment has been performed.

2.2. Data collection and analysis

During the 1-year monitoring, four key parameters of the coral fragments were analysed: i) growth rate; ii) survival rate; iii) presence of parasites; and iv) presence of diseases (including bleaching). During each underwater survey, the 242 fragments were measured by divers to the nearest millimetre with a Vernier calliper along the longest axis of the coral fragment to track their growth. The growth rate of corals (Gr) was calculated with the formula $Gr = T_2 - T_1$, where T_1 represents the measurement of the fragment at the time 1 and T_2 the measurement of the same fragment at the subsequent time 2. Monthly average growth rates were calculated with standard errors.

Coral mortality was assessed at each survey from the number of dead fragments with respect to the total number of fragments and then averaged over the months. The survival rate of corals was computed from the number of living coral fragments found at the end of the 1-year monitoring.

Photographs of each coral fragment were also taken from different angles during each monitoring time to assess the overall health state of the fragments. The presence of parasites and of signal of diseases were visually assessed from the analysis of photographs, and reported as the % of parasitized (or diseased) fragments found each month with respect to the total number of fragments. For each dead fragment the putative cause (i.e., parasites, diseases, or bleaching) was also defined.

According to [21], the health condition of each coral fragment was classified using 4 categories based on the amount of living tissue remaining on the fragment: 1) 100% of living tissue; 2) 100% > living tissue ≥ 50%; 3) < 50% of living tissue; and 4) pale or partially bleached fragment. The frequency of each category was measured every month.

To evaluate the effects of thermal stress on the fragments' state of health, the average monthly growth rate, the average coral mortality, and the average number of new diseased or parasitized corals per month were compared to the average monthly Sea Surface Temperature (SST) of the month before (under the hypothesis that corals need some weeks before reacting to thermal stress). Monthly average local SST data for the period December 2021 and October 2022 were obtained from the Maldives Meteorological Service, which has a station nearby Hululé Island, approximately 5 km distant from the restoration site. The average number of new diseased or parasitized corals per month were also compared to the average coral mortality. Correlations between all the investigated variables (growth rate, parasitized corals, diseased corals, local SST, and coral mortality) were perfromed using the Pearson correlation test with the Past3 software.

3. Results

3.1. Growth rate and thermal anomaly

Coral fragments reached the highest growth rate (0.38±0.03 cm) in the month of February 2022, two months after their translocation to the coral nursery (Figure 2). Then the coral growth started to decrease in parallel with the increase in the water temperature, reaching the lowest monthly growth rate in May (0.09±0.01 cm), just one months after the peack in the mean temperature of April (30±0.1°C) (Figure 2). After May, the growth of corals started to increase again until August (0.34±0.03 cm), in parallel with the decrease of the water temperature. During the last months of the monitoring period, coral growth maintained stable. A significant negative relationship was found between the monthly growth rate of coral fragments and the monthly local SST ($r = -0.71$, $n = 11$), being the temporal trend of the two variables specular (Figure 2).

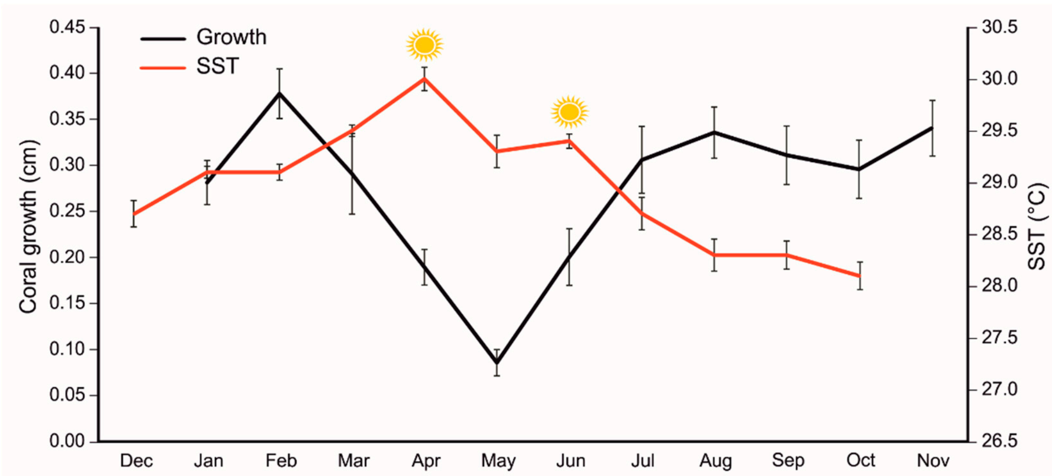

Figure 2. Mean (±se) values of the monthly growth rate of coral fragments in the nursery (black line) and mean (±se) values of the sea surface temperature (SST, red line). Symbols of suns represent the two peaks registered in the water temperature.

3.2. Survival rate, spreading of diseases and parasites

After 1-year of monitoring the final survival rate of 70.2% was registered. The highest percentage of coral mortality was reached in February (7% of the fragments), two months after the translocation of fragments to the coral nursery, and in October (7.9%), whilst in all the other months the coral mortality ranged between 0% and 5% (Figure 3a). A not significant relationship was found between coral mortality and water temperature ($r = -0.09$, $n = 11$).

Diseases were recorded in 53% of the coral fragments by the end of the monitoring period. The highest percentages of diseased corals were recorded in the first months after the translocation of fragments to the coral nursery, i.e. in January (9.5%), February (7.9%), March (9.1%), and May (8.3%), whilst in all the other months the percentage of diseased corals was lower and ranged between 0% and 4.5% (Figure 3b).

By the end of the monitoring period, 71.5% of the coral fragments presented at least one parasite. Parasites spread rapidly in the first four months after the translocation, between December and March, with a maximum number of new parasites recorded in March (14.9%) (Figure 3c). By June,

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61% of coral fragments were infested with parasites. Two different parasites were recognized in the coral fragments, i.e. Dendropoma maxima and Paguritta spp. Significant relationships were found between coral mortality and both diseased corals ($r = 0.63$, $n = 12$) and parasitized corals ($r = 0.75$, $n = 12$).

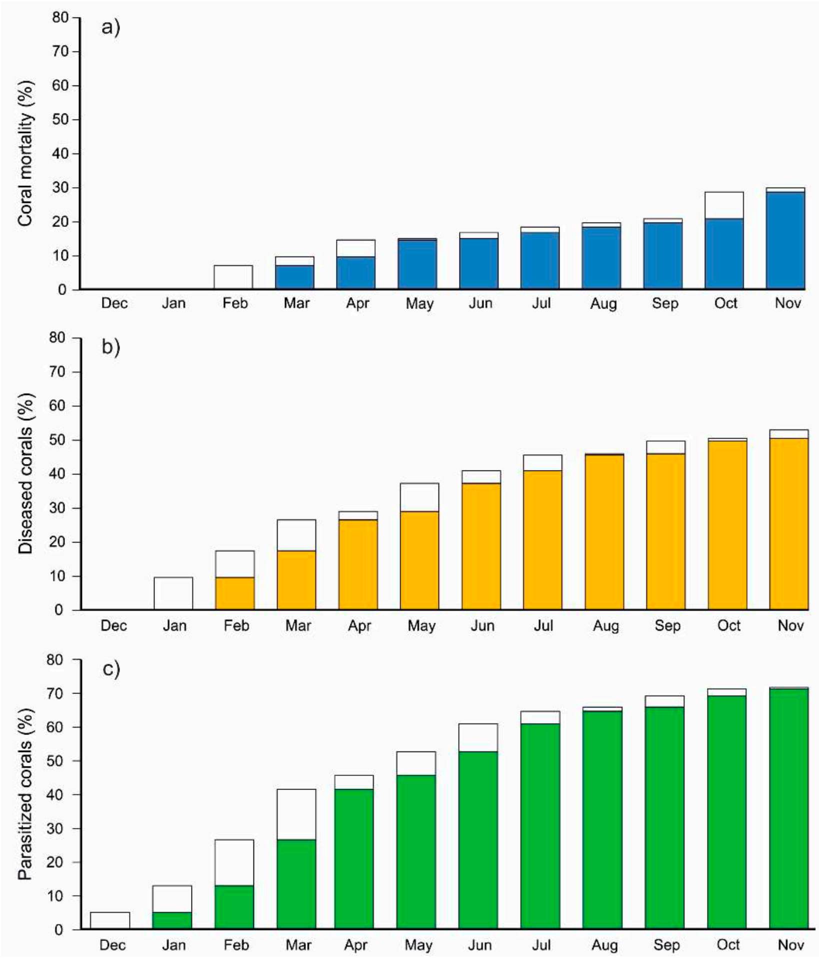

Figure 3. Cumulative monthly coral mortality (a), diseased corals (b), and parasitizes corals (c), expressed as the % of the total coral fragments. The white portions in the bars indicate the % of new dead coral fragments (a), new diseased fragments (b), and new parasitized fragments (c) found every month.

3.3. Health condition of coral fragments

The number of fragments with 100% of living tissue decreased to about 36% by the end of the year, whilst fragments with more than 50% living tissue became the dominant category from March till the end of the monitoring period (Figure 4). The frequency of fragments with less than 50% of living tissue started increasing in July. Frequency of paled and/or partially bleached fragments showed the highest values in December (27%), when the coral fragments were transferred to the nursery, and in April (20%), during the heat wave. From June their frequencies became negligible or absent.

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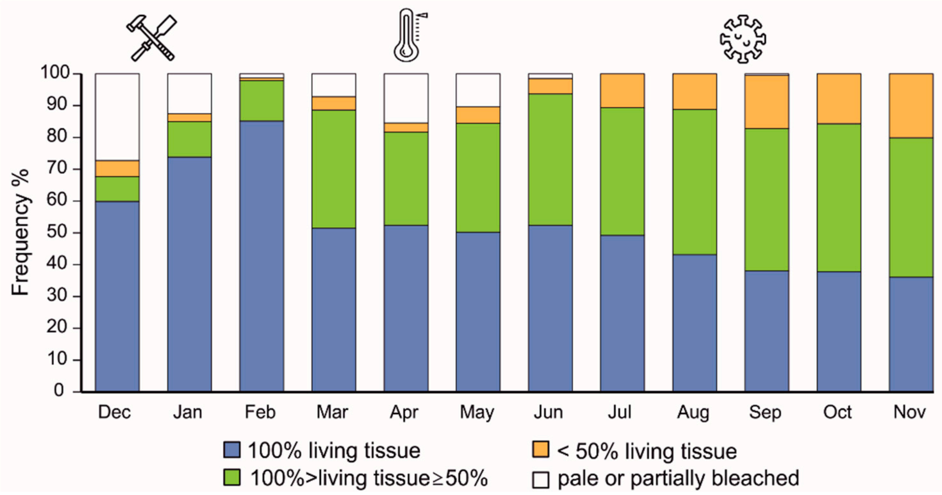

Figure 4. Frequency of each category of the health condition of coral fragments. The symbols on the top indicate the different stressors that affected coral fragments throughout the year: hammer and chisel indicate the mechanical stress resulting from the fragging and attaching of the fragments; thermometer indicates peaks in sea surface temperature; pathogen indicates spreading of diseases and parasites.

4. Discussion

In this study, a challenging experiment to restore a degraded coral reef in a highly impacted area of the Maldives was performed. Healthy coral fragments were collected from donor-impacted colonies and transferred to the nearby coral nursery to allow them to grow under controlled conditions. During the 1-year monitoring period, coral fragments were subject to a number of stressors, namely: i) mechanical stress due to fragging and translocation to the nursery; ii) thermal stress due to the heat wave that occurred 5 months later their translocation; iii) spread of parasites and diseases; and iv) overall poor water quality of the area. The survival rate recorded 1-year later was higher than 70%, indicative of the good resilience of coral fragments notwithstanding the various stress and disturbances that undermined their growth. Although this result is lower when compared to other examples of coral restoration performed in the Maldives [43,44], which had about 80-90% of survival after the first year, the location of Villimalè Island must be considered in the performance of the experiment.

Villemalé proximity to the capital city of Malè and to the garbage island of Thilafushi means a very poor water quality in this area. The high level of human pressures and the huge amount of pollutants found in its waters [40], make Villimalé a challenging location for corals to grow. The low monthly growth rate registered throughout the year (always < 0.4 cm) is likely to be due to the origin of the coral fragments from the impacted colonies of the donor reef, as well as to the local stressful conditions caused by the poor environmental status, as already shown by other studies [44–46]. It should therefore come as no surprise that any restoration program undertaken in these highly impacted locations could be slower and potentially less successful than in other less developed areas. The site-specific characteristics of the coral nursery contributed to the success of the restoration and must therefore be considered, especially during the project planning [44].

While dealing with local stressors, transplanted coral fragments also faced a severe heat wave that reached the country between March and April 2022. The increase in the SST also challenged the restored corals, causing a sharp decline in their growth rates for more than three months. Although coral growth has been significantly affected by the water temperature anomaly, it did not cause significant mortality of coral fragments. Fragments appeared pale or partially bleached from March to May, but they successfully recovered when the temperature returned to normal values, showing a high resilience to thermal stress even if the peak of 31.1°C reached by the SST in April exceeded the severe bleaching threshold [28]. Being thermal anomalies one of the most important drivers of coral mortality, results from our restoration experiment are promising and suggest that for planning successful restoration programs also the starting time of the translocation must be carefully selected to avoid those periods of the year more affected by thermal anomalies (i.e., from April to May in the Maldives). Corals are likely to be already acclimatized to the new environmental conditions after some months from the translocation and are thus able to better resist further stress.

Mortality of coral fragments (29.8% of the translocated fragments after 1 year) was mainly caused by the spread of diseases and parasites. Two main diseases on coral fragments were identified, i.e. the Skeletal Eroding Band disease [31] and the Stony-Coral-Tissue-Loss Disease [47]. The highest % of diseased corals was recorded in the first months after the translocation (from January to March), likely because the mechanical stress caused by the fragging and the attaching made the fragments more vulnerable to infection. This was also confirmed by the high frequency of pale or partially bleached fragments in these first months of the experiment. In addition, the polluted waters of the North Malé Area favoured a high presence of pathogens [31,44]. The extent and the frequency of coral diseases in the Indo-Pacific region have been shown to increase continuously, becoming an imperative environmental issue worldwide that will ask further investigation and conservation efforts [48]. This threat is also exacerbated by the instability of climate [49], which negatively affects coral reefs increasing pathogens' abundance and virulence [33] and, simultaneously, decreasing corals' resistance to pathogens.

Parasites spread rapidly since the fragments were translocated to the coral nursery and were similarly responsible for coral mortality, with more than 80% of parasitized colonies by the end of the year. Spreading of both diseases and parasites had the same peaks after 2-4 months from the translocation, confirming the susceptibility of stressed corals also for parasites. Infection by diseases is likely to reduce coral growth, making them more susceptible to the establishment of parasites. Parasite abundance has long been suggested as an indicator of ecosystem stress [50], and some species of parasites as bio-indicators of environmental degradation [51].

Coral fragmentation of diseased and impacted colonies showed effective to restore a highly degraded reef and represented a feasible mitigation measure for biodiversity conservation. Although the reduced growth of corals might require longer time before the new colonies will reach the adult stage and, eventually, will be ready for relocation in other reefs, this challenging approach could revolutionise the coral restoration of highly impacted reefs when the translocation of healthy coral colonies from donor reefs is not an option. Also, all the restoration activities carried out in this study required fewer resources and lower costs compared to the typical restoration approaches, making it a good option for small realities that, otherwise, may not have the means to restore their reefs. Locally tested methodologies and economically viable project designs should be more implemented rather than a single restoration approach scaled up [21]. Being the Maldives a country with few examples of coral restoration projects, especially in highly populated islands inhabited by local communities, these findings will be useful to involve the government in planning future restoration programs, mainly on those local islands with limited resources.

Cheap solutions for restoration interventions, along with community-based support, open the opportunity for a wide application of similar studies to restore highly impacted reefs that usually occur in the most populated tropical areas [52,53]. It is vital to act locally and reverse coral reef decline and biodiversity loss through coral restoration initiatives by enhancing coral resilience [18]. The human dimension is particularly relevant to coral restoration since people are involved in all stages of the process, from design to execution and monitoring [37]. The direct involvement of local communities and volunteers has the potential to improve local and global management of reef resources [54], increase awareness towards threats to coral reefs, and involve every citizen in helping to preserve and restore their reefs.

As a final remark, to ensure successful restoration interventions in highly anthropized and polluted areas, periodic monitoring activities for the maintenance of the nursery are mandatory, especially for cleaning the frames and ensuring the stability of the fragments on the substrate: without this effort, all the translocated coral colonies would have died before the end of the experiment.

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