Chapter 10

Multi-Disciplinary Lessons Learned from Low-Tech Coral Farming and Reef Rehabilitation: I. Best Management Practices

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Abstract

Low-tech coral farming and reef rehabilitation have become important community-based coral reef management tools. At least in the wider Caribbean region, these strategies have been successfully implemented to recover depleted populations of staghorn (*Acropora cervicornis*) and elkhorn coral (*A. palmata*). They have also been used with relative success to recover depleted fish assemblages. Indirectly, coral reef rehabilitation has also resulted in enhanced benthic spatial heterogeneity, in providing multiple new microhabitats for fish and invertebrate species; have contributed to the recovery of coastal resilience, increasing the protection of shorelines against erosion; and have fostered an increased interest of the tourism sector as an enhanced attraction for visitors and recreationists. Nevertheless, there is still a need to implement best management practices to improve the success of these strategies. In this chapter, lessons learned from the *Community-Based Coral Aquaculture and Reef Rehabilitation Program* in Culebra Island, Puerto Rico, are shared from a multi-disciplinary standpoint. Learning from past experiences is a critical process to improve science. In a time of significant projected climate change impacts and sea level rise, improving the scale of coral farming and reef rehabilitation has become a critical tool for coral reef conservation. But multiple roadblocks must still be overcome.

Keywords: coral farming, coral reefs, ecological rehabilitation, lessons learned, Puerto Rico, Caribbean Sea, reef fish communities, threatened coral species

1. Introduction

1.1. Coral reef decline and the emergent role of ecological restoration as a management tool

Coral reefs have largely declined across regional and global scales over the last four to five decades as a combined result of multiple local, regional, and global human stressors. Local stressors are factors that affect ecological processes which occur within reef communities and often include water quality degradation [1], eutrophication [2], sedimentation [3], turbidity [4, 5], fishing [6, 7], blast fishing [8], vessel groundings [9], military training activities [10], and recreational abuse [11, 12], among many others. Regional-to-global scale stressors are climate change related, including sea surface warming [13, 14], massive coral bleaching [15, 16], disease outbreaks [17, 18], mass coral mortalities [19, 20], and its concomitant effect in reef fish assemblages [21]. Ocean acidification [22], in combination with eutrophication [23], has been shown to accelerate coral diseases and erode overall reef resilience [24]. Bioerosion has also become a key widespread process that, in combination with rapidly declining reefs, eutrophication, and ocean acidification, represents an increasing threat, though data on actual bioerosion rates are limited to a few well-studied cases [25]. In addition, hurricanes have become a significant concern in the Atlantic due to their apparent link to increasing climate change impacts [26–28]. Such multiple combined interactions have contributed to the large-scale demise of coral reef ecosystem resilience, compromising their capacity to sustain ecosystem services; threatening the sustainability of reef fisheries, its productivity, and its ability to produce food protein to feed hundreds of millions of people; and protecting shorelines from erosion, unless trends are otherwise reversed [29].

Indo-Pacific coral reefs have shown significant declines following past disturbances [30, 31], but have shown rapid signs of recovery, often within decadal time scales [32–34]. However, Caribbean coral reef ecosystems have also shown significant impacts [20, 21], but very limited natural recovery [7, 35]. Instead, Caribbean coral reef benthic communities have shown a rapidly shifting trajectory from coral dominance to dominance by non-reef-building taxa, mostly macroalgae [36–38]. Recent coral recruitment trends also point out at a shifting trajectory and dominance by small-sized, ephemeral species [39]. Limited natural recovery ability and shifting benthic community trajectories are the direct result of limited functional redundancy of Caribbean reef ecosystems, in comparison to their Indo-Pacific counterparts [40]. Such declining trends may imply the onset of permanent alterations on ecosystem resilience and persistence, ecological functions, values, and benefits. Therefore, reef ecosystems are shifting into what has been designated as novel ecosystems [41–45], with often significantly altered biological assemblages and ecological functions, and yet unknown long-term effects on ecosystem composition, functions, and productivity. This makes necessary to examine the role of assisted recovery of depleted coral diversity, restoring coral functional groups, and the rehabilitation of coral reefs at the reefscape, functional level, as a new strategy to buffer and restore present declining trends.

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Multiple low-tech coral farming and reef rehabilitation efforts have proliferated across a global scale over the past 10–15 years with the aim to foster a rapid recovery of depleted coral species [46–51] and to recover reef structure, function, and ecosystem services [52]. However, most of these experiments have been of very limited spatial scales (often <100 m^{-2}) and often of very short duration (<1 y) [53–61]. Therefore, impacts have been of very limited ecological significance. Nevertheless, multiple methods have shown to be promising as future tools for depleted coral species restoration, for the rehabilitation of reef's ecosystem functions and services, and for recovering coastal resilience. But there is still a general lack of published systematized information regarding lessons learned from such activities that could serve as a step-by-step guide for coral reef managers to restore depleted coral reefs. Reviews on coral farming strategies to replenish degraded coral reefs are still scarce and have focused on very limited questions and geographical scales [47, 49, 50], on the role of integrating habitat enhancement to aquaculture and fisheries management [62], and on the potential benefits to habitat conservation [51, 63]. However, there is still a general lack of published systematized information regarding lessons learned from such activities that could serve as a step-by-step guide for coral reef managers to restore depleted coral reefs.

1.2. Goals and objectives

The goal of this chapter is to briefly update the state of knowledge regarding low-tech coral farming efforts around the globe and address a wide range of multi-disciplinary lessons learned through the 15-year-old *Community-Based Coral Aquaculture and Reef Rehabilitation Program* led in Puerto Rico by NGO Sociedad Ambiente Marino, with the collaboration of the Center for Applied Tropical Ecology and Conservation of the University of Puerto Rico. Lessons learned cover topics regarding: coral biology; the science of coral collection, handling, transporting, and out-planting to farming units; maintenance; long-term monitoring of corals in farms; out-planting site selection and methods; and the long-term monitoring of coral out-plants. Finally, the chapter also included a discussion on general recommendations and needs for implementing best management practices.

2. State of knowledge in the development of low-tech coral farming and reef rehabilitation

The state of knowledge regarding the development of low-tech coral farming and reef rehabilitation has largely expanded across the globe during the recent two decades. **Table 1** summarizes some of the recent efforts across different geographical areas. Pioneering work commenced across the Caribbean due to its limited natural recovery ability and the need to implement low-tech reef restoration efforts. But a suite of different methods has been developed across the globe involving multiple benthic coral culture units, floating units, rope nurseries, and combinations of these. Also, different methods have been implemented for

Location	Method	Survival	Time (m)	Reference
Israel	Cement tiles; plastic net	25–83% fragments *Stylophora pistillata*, 6 m, cement tiles, site-specific 83%, 6 m; 61%, 18 m; plastic net	6–18 m	[64]
Egypt	Plastic mesh	14–48% without epoxy, species-specific	6 m	[65]
		86–91% with epoxy, species-specific	12 m	
		8–11% without epoxy, species-specific		
		11–21% with epoxy, species-specific		
Japan	Concrete armor blocks	15–20% species-specific	20 m	[66]
Philippines	Concrete blocks	ND	12 m	[67]
Singapore	Table nursery; plastic mesh	34%	14 m	[68]
Palau	Pushmounts for coral spat	73–80%; asexual fragments *Acropora digitifera*, *A. hyacinthus*	18 m	[69]
	Plastic ties and pushmounts for fragments	14–24%; after sexual larval settlement	12 m	
Indonesia	Cathode and electric field	68%; *Acropora yongei* in cathode wire; 99% in electric field and in control	4 m	[70]
		83%; *A. pulchra* in cathode wire; 91% in electric field, and 87% in control		
Puerto Rico and Pohnpei, Micronesia	Lose fragments Fragments attached to a fishing line in the bottom	Survival in *A. cervicornis* and *A. prolifera* strongly treatment and size dependent. 0% in fragments 8–12 cm; 95% in fragments >30 cm	3	[74]
Puerto Rico		Survival treatment, size and location dependent: *Acropora cervicornis*	6	[73]
		3–5 cm 70%; 8–12 cm 80%; 15–22 cm 95% in backreef areas;3–5 cm 50%; 8–12 cm 90%; 15–22 cm 95% in reef front areas; *A. prolifera*—3–5 cm 80%; 8–12 cm 70%; 15–22 cm 70%		
Puerto Rico	Wire mesh “A frames”; Horizontal line nurseries (HLN)	Survival rate in *A. cervicornis* “A frame” units strongly dependent on method and exposure to extreme rainfall and runoff; “A frames” 73% in 2011–2012; 81% in 2012–2013; 97% in HLN in 2012–2013	24	[80]

ND, no data.

Table 1. Global-scale variation in coral farming and reef restoration methods.

out-planting activities, involving the use of masonry nails and plastic ties, as well as the use of different artificial substrates used for compensatory mitigations of environmental impacts or for habitat enhancement. However, coral colony survival rates either during coral farming or after out-planting to natural reefs have been largely variable and often species-, size-, and site-specific. Nevertheless, low-tech methods have been successfully implemented with the participation of base communities across multiple locations.

The use of wild and/or captive-bred coral larvae is also a promising alternative for coral propagation without compromising source population fitness [71]. However, such methods involve high tech, more expensive methods, equipment, and laboratory facilities. They also require highly trained scientific personnel, with limited possibilities of involving base communities in the process, unless extensive technical training has been provided to participants. Recent advances integrating population genetic structure of corals and holosymbionts have also pointed out the importance of collecting a genetically diverse nursery stock and of maintaining poor-performing holobionts in culture to avoid selecting only nursery-fit genets [72]. Alternatively, nurseries may be established in multiple habitat types to maintain a wide range of holobiont types acclimatized to different environmental conditions. Probably, the most significant advantage of high-tech propagation strategies is the ability to propagate *ex situ* significant amounts of coral spat during each reproductive cycle. Further, *ex situ* propagation in flow tanks can have the potential to produce 100–1000 of small coral fragments (e.g., sizes of only a few polyps) several times per year. The combination of low-tech and high-tech, genetic-based propagation strategies can lead to enhance coral propagation and out-planting success across multiple coral reef locations. With improved capabilities of long-distance transportation, these methods can also improve the ability to restore multiple locations within shorter time scales. Long-distance transportation may imply hours to several days, depending on distance of source coral reefs and on logistics of transportation. It may require developing simple to sophisticated methods of keeping corals wet, aerated, and protected from direct sunlight and high temperature. Providing mechanisms such as plastic buckets or coolers provided with a battery-powered water pump and a small PVC pipe system with multiple small holes drilled on them to allow water to sprinkle corals will allow to keep them wet during prolonged transportation. But using a Z-shaped 2″ PVC pipe in a vessel can allow natural pumping of oxygenated seawater to sprinkle corals during the ride. If a cooler is used, it can also be provided with a battery-powered chiller and an air pump. Previous experience in Puerto Rico using such battery-powered systems has allowed transportation of corals of up to 11 h from source to farming site and involving multiple transportation systems (e.g., small boat, vehicle, ferry, and another small boat). This effort resulted in a 100% survival rate, with no stress to out-planted staghorn coral (*Acropora cervicornis*) and to fused staghorn coral (*Acropora prolifera*).

2.1. A quick glimpse of previous successful experiences in Puerto Rico

Coral farming and reef rehabilitation science in Puerto Rico evolved since year 1980 with low-scale pioneering experiments by Carlos Goenaga and Vance Vicente in Cayo Enrique reef, La Parguera. However, that experiment, though successful, generated no publications. Then, by 1993, Austin Bowden-Kerby developed low-tech coral farming and reef restoration work involving staghorn coral (*A. cervicornis*) and fused staghorn coral (*A. prolifera*) [73, 74]. Ortiz-Prosper et al. [75] in 1998 out-planted corals to reef ball artificial units and to dead coral surfaces. Sociedad Ambiente Marino (SAM), in collaboration with Culebra Fishers Association and Correlations, established in 2003 the *Community-Based Coral Aquaculture and Reef Rehabilitation*

Program in Culebra Island, with over 60,000 staghorn coral colonies out-planted in 15 years [76–80]. Elkhorn coral (*Acropora palmata*) out-planting under high wave energy conditions has been successfully conducted at Vega Baja since 2008 by Vegabajeños Impulsando Desarrollo Ambiental Sustentable (VIDAS) and SAM [76]. Additional work with extensive out-planting of staghorn coral has been conducted in southwestern Puerto Rico and more recently in northeastern Puerto Rico by the National Oceanic and Atmospheric Administration—Restoration Center (NOAA-RC) and by Sea Ventures [81, 82]. Additional coral farming and out-planting has been carried out since 2010 in southwestern Puerto Rico by HRJ Reefscaping in collaboration with NOAA-RC. Another important coral restoration effort was conducted by NOAA at Mona Island following a major vessel grounding in 1997 [83, 84]. Recent smaller efforts have also been developed across the northern coast of Puerto Rico by NOAA-RC and VIDAS.

In summary, a suite of methods is currently being successfully implemented in Puerto Rico involving multiple locations (**Figure 1**) and a variety of methods (**Figures 2** and **3**). Similarly, a combination of low-tech approaches has been implemented during coral out-planting on natural depauperate reef substrates. The longest continuous coral farming and reef restoration project is led by SAM in Culebra Island (since 2003), with the close collaboration of the University of Puerto Rico's Center for Applied Tropical Ecology and Conservation (CATEC). VIDAS has led the Vega Baja restoration project since 2008. HJR Reefscaping has led projects along southwestern Puerto Rico. NOAA-RC has led and/or collaborated with basically all other initiatives. Also, the agency has led multiple reef restoration efforts across the U.S. Virgin Islands and Florida, USA. All of the above-listed efforts have placed Puerto Rico at the top leading role of coral reef restoration and rehabilitation efforts across the northeastern Caribbean region (**Figure 4**).

Figure 1. Active coral farming and reef restoration sites in Puerto Rico. From northwest to northeast: Isabela; Arecibo; Vega Baja-Manatí; Arrecifes La Cordillera Natural Reserve, Fajardo (Cayo Diablo, Palominos Island); Canal Luis Peña Natural Reserve, Culebra (Bahía Tamarindo, Punta Tamarindo Chico); and Punta Soldado, Culebra. From southwest to east: La Parguera Natural Reserve, La Parguera (San Cristobal, El Mario); Guánica Biosphere Reserve, Guayanilla; and Caja de Muerto Natural Reserve, Ponce.

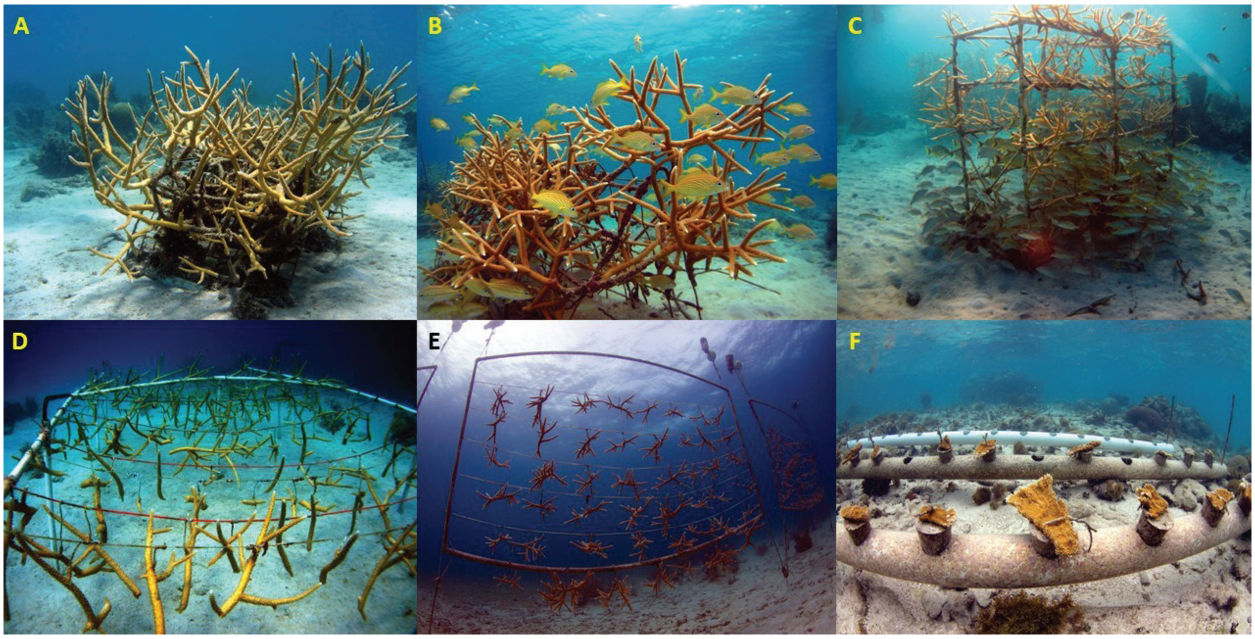

Figure 2. Examples of low-tech coral farming methods used in Puerto Rico. From top left: (A) plastic-covered wire mesh; (B) large wire mesh; (C) COndominium pvc unit; (D) horizontal line nursery; (E) floating underwater coral array (FUCA); and (F) benthic underwater coral array (BUCA). The first five models have been used with staghorn coral (*Acropora cervicornis*) and fused staghorn coral (*A. prolifera*). The BUCA has been used for elkhorn coral (*A. palmata*).

Figure 3. Examples of additional low-tech coral farming methods used in Puerto Rico. From top left: (A) pvc plastic grid; (B) "cathedral" line nursery; (C) tree unit; (D) modified benthic underwater coral array (m-BUCA); (E) concrete cookies; and (F) tree unit. Models A and B have been used with staghorn coral (*Acropora cervicornis*). Models C–E have been used with elkhorn coral (*A. palmata*). Model F has also been used with pillar coral (*Dendrogyra cylindrus*) and star coral (*Orbicella faveolata*).

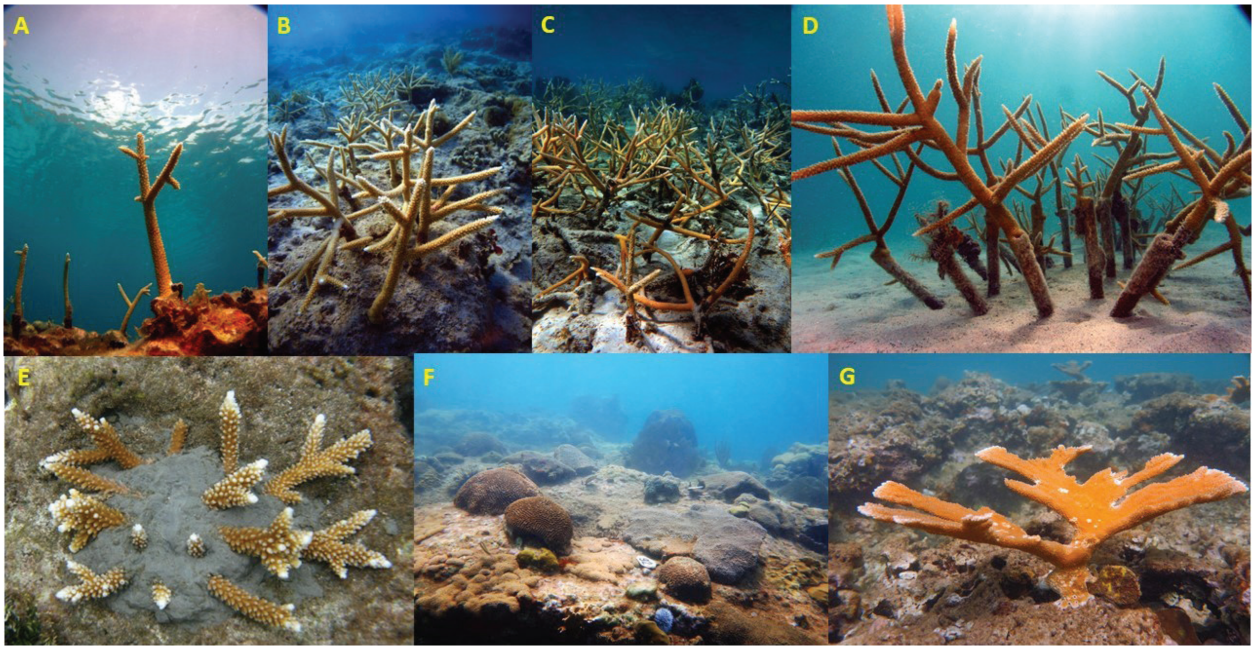

Figure 4. Examples of low-tech coral out-planting methods used in Puerto Rico. From top left: (A) out-planting of *Acropora cervicornis* on top of dead coral heads; (B) and (C) creation of *A. cervicornis* thickets on formerly bombarded, flattened coral reefs in Culebra Island; (D) creation of semi-natural reef corridors of *A. cervicornis* using concrete bases and pvc plastic sticks to attach corals on open sandy bottoms; (E) *A. cervicornis* "flower pots" on open reef substrates; (F) reconstruction of reef's seascape with brain coral (*Pseudodiploria strigosa*) using concrete on natural open reef surface; and (G) 3-year-old out-planted *A. palmata* after wedging a fragment on a natural reef crack.

2.2. Limitation of previous efforts

The most significant limitation of previous efforts, not only in Puerto Rico, but also across the wider Caribbean region and across other locations around the world, has been the still small spatial scales impacted by ecological restoration efforts. Most projects have often been limited to the scale of 10–100 m^2. A combination of factors can limit the spatial scale of such endeavors, including: (a) limited economic, technological, and/or human resources; (b) limited source propagules; and (c) still limited success of larval-rearing methods. Many projects have often been experimental test beds for methods development, for methods demonstration, for mitigating specific environmental impacts (e.g., vessel grounding, storm/winter swell impacts, construction projects), or to address specific research questions. Many of these have shown promising success. However, their applicability to larger spatial scales still remains a question. This has led many detractors of ecological restoration to question, denigrate, or mock applied restoration ecologists, managers, practitioners, and NGO and community-based volunteers for "wasting money, time and efforts" in attempting to restore coral reefs through coral farming and other methods.

Coral farming and reef restoration have been successful at the scales so far implemented. But in order to become meaningful at ecological spatial scales, there is a need to improve spatial scales of future projects. This needs to include aspects such as: (a) increasing ecological and genetical connectivity to improve, for instance, fish assemblages spatial connectivity and functional redundancy; (b) rehabilitating benthic spatial heterogeneity to recover benthic microhabitats (e.g., shelter, foraging, and feeding grounds) for multiple species; and (c) rehabilitating overall coastal resilience, ecological services, and benefits (e.g., wave buffering role, nursery ground roles, landscape restoration to improve tourism and recreational value). This will require new fundraising strategies, as well as creative strategies for partnerships development, for engaging, educating, and training NGO and community-based volunteers, and for establishing a functional relationship between government agencies, academic institutions, industry, private business, and other community-based stakeholders. There might also be a need to combine low-tech with high-tech methods in an attempt to significantly improve the number of coral propagules for restoration. This may require novel international cooperative agreements for coral propagule sharing and exchange. This may even have the benefit of increasing local genetic diversity. Moreover, in many instances, there might still be a need to develop public policy and a vision in regards to coral reef conservation and ecological restoration to lead future efforts. Otherwise, successfully enhancing reef restoration spatial scales might remain a difficult task.

2.3. Benefits of reef rehabilitation

Low-tech coral farming and reef rehabilitation can have multiple local (**Table 2**) and regional (**Table 3**) ecological benefits, as well as multiple socio-economic and educational benefits (**Table 4**). Most of the benefits are derived from those previously described for marine protected areas [85]. The evaluation of reef rehabilitation benefits is often limited to immediate

Restoration criteria	Summary of benefits
Conservation	Propagation and reintroduction of largely depleted coral species which otherwise will have a very low probability of having successful sexual reproduction and colonization. Increased coral density to foster the recovery of coral reproduction potential at local scales and buffer the impact of reproductive isolation (Allee effects)
Reef accretion	Foster reef bio-construction by propagating and out-planting rapid-growing ecosystem engineer coral species. The reintroduction of rapid-growing coral species is aimed at helping local coral reef ecosystems to rapidly increase accretion rates, rehabilitate fish and invertebrate shallow-water nursery grounds, restore reef’s wave buffering role, and adapt to projected rapid sea level rise
Habitat structural complexity	Rapid-growing coral species also help in the natural rehabilitation of benthic habitat structural complexity, which provides shelter to a myriad of reef demersal species
Biodiversity	Help replenish coral reef-associated biodiversity (e.g., fish, invertebrate species and functional groups) that use Acroporid biotopes as nursery, shelter and feeding grounds, and attract larger predators
Genetic resilience	Contribute to maintain and restore genetic diversity of targeted restored coral species by fostering reintroduction of multiple genetic clones, fostering genetic recombination on local scales, and promoting enhanced sexual recruitment on adjacent coral reefs by increasing ecological connectivity
Ecological functions	Rehabilitate coral functional redundancy as fish nursery grounds by improving benthic habitat complexity and restoring its function as fish and invertebrate habitat

Table 2. Local benefits from community-based coral farming and reef rehabilitation in face of climate change.

Restoration criteria	Summary of benefits
Uniqueness	Whether a restored area is "one of a kind" (e.g., habitats of endangered or rare species). Rehabilitated reef habitats with rare and/or threatened coral species can rapidly become a unique biological community with paramount significance across local, national, and regional scales because of its unique biological features, ecological functions, and critical genetic connectivity value
Naturalness	Degree to which the restored area helps in the recovery of reef's naturalness or lack of disturbance or degradation. Control or elimination of anthropogenic disturbance signals (e.g., overfishing, sedimentation, turbidity, pollution, anchoring, excessive SCUBA diving, rapidly declining coral cover). Areas with restored natural seascapes
Dependency	Degree to which a species or a group of species depend on a restored area. Degree to which an ecosystem depends on ecological processes occurring within the restored area. Enhanced ecological functions on local scales and recovered functional redundancy will benefit overall reef ecosystem functions
Representativeness	Degree to which a restored area represents a habitat type, ecological processes, biological community, geological features, or other natural characteristics, including the role as refuge for threatened or rare species
Integrity	Degree to which a restored area is a functional unit or an effective, self-sustaining ecological entity (e.g., a restored coral population undergoing annual sexual reproduction and functioning as recruiting and/or shelter, or feeding habitat for multiple species). Degree to which a restored area functions as a biological corridor between adjacent reefs, improving ecological connectivity
Productivity	Degree to which the productive processes within a restored area contribute benefits to adjacent reefs (e.g., fostering coral larval recruitment, fish spillover effects to other reef species). This can be achieved through enhancing recruitment, shelter, and/or feeding habitat. It can also benefit humans (e.g., ability of any given restored site to contribute to the sustainability of local fisheries either as a nursery ground or through the rehabilitation of important historical or traditional artisanal fishing grounds)
Connectivity	Degree to which a restored area is physically connected to other areas. Degree of connectivity between colonies of any given species at other areas via surface currents. The rehabilitation of critically located coral reefs will foster increased gamete and larval production of replenished coral species fostering potential higher recolonization of "downstream" reefs. Restored reefs will also foster similar effects for many fish and invertebrate species through spillover effects or mass spawning. The establishment of networks of restored reefs will improve the restoration success and connectivity effects on adjacent reefs
Regional significance	Degree to which the restored area represents a restored characteristic of the region or the degree to which the restored area fills a gap in a network of protected areas from the regional or sub-regional perspective. The larger the restored reefs network is, the larger the regional significance

Table 3. Regional benefits from community-based coral farming and reef rehabilitation in face of climate change.

components such as coral percent survival and growth rates. However, benefits to local components, such as conservation, reef accretion, habitat structural complexity, biodiversity, genetic resilience, and ecological functions, still remain poorly documented. Similarly, regional-scale factors, such as uniqueness, naturalness, dependency, representativeness, integrity, productivity, connectivity, and regional significance, are also limited. Furthermore, there are multiple socio-economic benefits, such as the role of reef rehabilitation as a climate change adaptation tool to increment carbon sequestration through calcium carbonate ($CaCO_3$) precipitation for

Restoration criteria	Summary of benefits
Climate change adaptation	Rearing and propagation of high-temperature resistant, highly resilient, coral genetic clones with a higher ability to resist and recover from massive bleaching events will help improve overall reef ecosystem's resilience to future bleaching events
Reconstruction of physically destroyed reef structure	Foster the seascape-level reconstruction of bomb-cratered, physically demolished, and coral-depleted reefs, with the aim of fostering the rapid recovery of coral reef functions and ecological services
Ecological services	Increased coral densities will help to improve reef's greenhouse gases buffering role, its natural breakwater function, particularly during storm and hurricane swells, its natural pharmacy function (source of natural products of bio-medical significance), and will improve reef-based fisheries productivity. If reef rehabilitation is carried out within a no-take reserve, it will further foster larger fisheries productivity and a spillover effect favoring fisheries productivity across adjacent habitats open to fishing
Socio-economic benefits of improving costal resilience	Degree to which certain commercially important species depend on a restored area. Degree to which a restored area plays an important link to adjacent fisheries. Degree to which reef restoration will impact the local economy in the long term and improve existing or potential socio-economic value of an area for tourism and recreational activities. Degree to which reef restoration fosters the recovery of reef-based fisheries, improving catches on adjacent reefs, benefiting local artisanal fishers, and improving their livelihoods
Education and outreach	Reef rehabilitation provides a useful hands-on, transformative educational tool aimed at empowering local base-communities to manage their coral reefs and carry out coral farming and reef rehabilitation in face of projected climate change impacts
Community-based adaptation to climate change	Degree to which base communities educate, integrate into decision-making processes, become technically trained in coral farming and reef restoration methods, and become better adapted to manage their local coral reef resources under challenging scenarios of climate change

Table 4. Socio-economic and educational benefits from community-based coral farming and reef rehabilitation in face of climate change.

coral growth; to reconstruct a physically destroyed reef structure; to recover ecological services (e.g., essential fish habitat role), socio-economic benefits of improving coastal resilience, education and outreach, and community-based adaptation to climate change, which have been seldom addressed. These components should be thoroughly addressed in the future.

Knowledge regarding low-tech coral farming and reef rehabilitation has rapidly advanced in recent decades, but much more attention should be paid to expanding spatial scales of ecological rehabilitation, increasing the diversity of grown corals, exploring new methods, and improving the understanding of their long-term benefits as a tool to recover ecological functions in novel ecosystems and to restore coastal resilience in a time of major environmental and climate changes.

3. Lessons learned from coral farming in Puerto Rico

A suite of lesson-learning experiences in Puerto Rico has provided useful recommendations for managers to adaptively modify management actions, review, and amend existing marine protected areas management plans and to develop a set of minimum guidelines to drive future management-oriented decision-making processes, including reef restoration efforts. This will allow to maximize their ecosystem-level impacts, while at the same time address emerging threats and integrate challenging multi-disciplinary ecological paradigms into day-to-day management actions. The development of low-tech coral farming and reef rehabilitation methods has provided novel low-tech management tools to shape future efforts to recover fish communities, herbivore fish guilds, and long-spine sea urchin densities; reduce macroalgal cover; and recover coral densities and percent living cover. It has also provided guidance to reef managers and decision-makers regarding the ecosystem-level benefits of coral farming and reef restoration efforts. This can further allow the delineation of specific guidelines to implement future reef restoration efforts across the Caribbean region to promote cost-effective ecosystem-scale recovery. This will foster enhanced ecosystem resilience under increasing threats by local human-driven factors and climate change. Furthermore, it will provide the multi-disciplinary basis for addressing the emergent challenge of addressing novel coral reef ecosystem-based fisheries management, climate change-related impacts, community-based integration, and the development of conceptual models to address future multi-disciplinary social-ecological management challenges. Nevertheless, there are specific lessons learned directly associated to coral farming and out-planting activities that will provide specific guidance to managers and practitioners.

3.1. Siting of coral farms

Site selection for establishing either coral farms or out-planting locations is a critical step. In order to fully recover structural and functional characteristics of a degraded ecosystem, more research is needed for the selection of suitable transplant sites (e.g., optimum substrate characteristics; physical stability, exposure to wave action, optimum population λ). It is also paramount to address ecological factors that might stress out coral out-plants and affect their survival and growth (e.g., low percent cover or absence of red encrusting algae *Ramicrusta textilis*, sediment input and bedload, exposure to runoff and pollution). Another critical lesson learned in Puerto Rico was the need to avoid areas exposed to urban runoff, human trampling, and uncontrolled recreational impacts (e.g., snorkeling, SCUBA diving, kayaking, shore-based fishing, recreational navigation, and anchoring). Even "low-impact" nature-based recreational activities can have highly localized adverse impacts on shallow-water coral farms and reef restoration sites due to coral colony fragmentation and dislodgment.

3.2. Low-tech materials and design

A key component to low-tech approaches is maintaining a cost-effective operation, with multiple benefits and high success rates. Low-tech methods often involve the creative use of readily available, cheap materials to support *in situ* coral farms. Multiple coral farming unit designs have been successfully used in Puerto Rico involving the use of pvc plastic pipes, fishing lines, plastic-covered wire mesh, and concrete. There is not a specific universal method to meet all needs or that can be suitable for all locations. Factors such as wave action, surface current exposure, sediment dynamics, depth, visibility, and coral species to be used can be critical determinants of the methods to be implemented. However, there is evidence that horizontal line nurseries are highly successful in terms of coral colony percent survival rate, live tissue cover, and skeletal growth rate, when compared to colonies grown in wire mesh units [76, 80]. Coral colonies grown in line nurseries and other types of floating units often show faster growth rates, show lower living tissue lesions, and do better when out-planted to natural reef surfaces. Coral farming unit design is a function of specific local needs, available resources, projected number of coral propagules, projected coral reef restoration efforts, objectives of the restoration plan, size of source wild coral populations, and other logistical constraints. The latter may include: environmental conditions of the selected coral farming site, distance from source coral populations, availability of trained personnel, funding limitations, and other factors. But, in the long run, the local availability of materials can be the main factor influencing the final decision.

3.3. Timing of coral farming activities

It is critical that coral transplanting, unless necessary as an emergency restoration measure, avoids the warmest months. Survival rate shows a significant reduction during the late summer and early fall months due to a combination of impacts associated to high sea surface temperature, major runoff impacts, major risk of disease outbreaks, and the risk of bleaching. Most coral out-planting should be planned for winter and spring months to increase survival rates.

3.4. Collection of coral fragments

3.4.1. Avoidance of negative impacts on wild donor colonies

It is fundamental to reduce negative impacts of collections on wild donor coral colonies. Collection of coral fragments should be limited to 10–15% of the donor colony volume or surface area. No mortality or reduced growth should result in donor colonies due directly to fragmentation. In the case of branching corals, tissue regeneration at the breaking points should occur within 2–3 weeks, and branch growth should resume within a month. Impacts should be monitored at least for 3 months by direct comparison of a representative selection of donor colonies and adjacent control unaltered colonies and by looking at percent mortality, tissue regeneration rate, growth rate, and branchiness index (branch production). For larger foliose, plate, or massive colonies, donor colonies should be monitored for 6 months to a year as tissue regeneration, and skeletal regrowth is slower.

3.5. Transportation, handling, and out-planting

Transportation should always be conducted avoiding coral exposure to direct sunlight and warm temperatures. For short distances, colonies can be transported under subaerial exposure, but under humid conditions (e.g., under wet towels, under a saltwater sprinkler, etc.). But for longer distance travel, a water tank should be used provided with an air pump, water pump, and chiller to control temperature.

3.6. Local benefits

The major local relevance of coral farming activities in Puerto Rico has been the continuous expansion of staghorn coral (*A. cervicornis*) and elkhorn coral (*A. palmata*) low-tech restoration efforts in Culebra Island, Fajardo, Vega Baja, and multiple other locations. This has been achieved through an integrated effort of the different practitioners, NGOs, the Puerto Rico

Department of Natural and Environmental Resources (PRDNER) and NOAA-RC. Strengthening collaboration, communication, and sharing of lessons learning experiences among all engaged stakeholders has been a key for success, as well as for improving support and volunteer collaboration among groups. This has also allowed to significantly increase the number of harvested colonies available for future reef restoration efforts. In addition, during recent years, there has also been an increase in the number of new community-based volunteers technically trained in coral transplanting, coral harvesting, and farm maintenance to collaborate at all project sites. In the particular case of NGO SAM, this experience was also used to successfully train volunteers at the Dominican Republic, resulting in the development of a long-term coral farming program at Punta Cana.

Direct benefit	Added values
Enhance public presence and leading role of NGOs and the academia addressing coral reef conservation issues	Strengthen out the Caribbean-wide leading role of PR as a model for the development of effective strategies for the multi-disciplinary integration of different sectors in the mitigation and adaptation to climate change impacts. Presence on the community can be achieved by multiple outreach activities by project's personnel, including seminars, information dissemination through the web, and mass media articles
Increase number of trained and educated professionals and students	Provide direct support and the basic framework for providing hands-on education and technical training to graduate and undergraduate research students regarding marine biodiversity conservation, coral farming, and reef ecological rehabilitation in the context of climate change impacts. This may also provide theoretical and hands-on practical training on coral reef conservation, coral farming, reef rehabilitation and monitoring, and coral demographic data processing, analysis, and interpretation
Increase number of trained and educated stakeholders	Provide hands-on education and technical training to community-based volunteer personnel through community-based organizations regarding marine biodiversity conservation, coral farming, and reef ecological rehabilitation in the context of climate change impacts
Empowerment for collaborative management	Project's participants (academic, community-based) acquire the necessary knowledge, skills, and experience to support government efforts to manage coral reefs resources through a collaborative, participatory model
Advance the implementation of a no-take marine protected areas management plans	Advance the implementation of no-take MPA management plans in support of government efforts
Advance NOAA Habitat Focus Areas goals	In the particular case of Puerto Rico, reef rehabilitation can achieve the NOAA Habitat Focus Areas goal of sustaining resilient and thriving marine and coastal resources, communities, and economies by addressing a habitat-based issue/concern contributing to the loss or deterioration of coastal resiliency or marine habitats for target managed or protected coral species
Fill critical data gaps for resource managers and decision-makers	Advance knowledge and help fill critical qualitative and quantitative information gaps about ESA-listed coral species across the U.S. Caribbean to support the implementation of management strategies aimed at the recovery of their depleted populations
Coral reproduction (=net reef accretion)	Increase coral out-planting across reef-seascape scales to increase local reproductive populations of depleted species across different coral reef. In the long-term, this will foster increased reef accretion rates
Fish productivity	Increase reef accretion to enhance benthic spatial heterogeneity and the rapid rehabilitation of fish communities mostly by fostering increased fish recruitment and by enhancing herbivore guilds. These are important steps towards recovering connectivity and ecosystem resilience

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Direct benefit	Added values
Connectivity (=buffer against further decline)	Increase number of rehabilitated reef patches to increase genetic connectivity across reef seascape scales. In the long term, this will increase connectivity with other coral reefs across ecological to regional scales
Coastal resilience	Increase coral density, wave buffering role, genetic connectivity, recover fish communities, and rehabilitate herbivory levels to help recover coastal resilience
Ecosystem resistance to future disturbances	Increase ecosystem resilience to foster an increased resistance to future disturbances (e.g., hurricanes). This is important for the sustainability of reef's ecological functions, goods, benefits, and services
Buffering of sea level rise (SLR) associated shoreline erosion	A rehabilitated coral reef should also recover its natural accretion rates to cope with increasing SLR and its concomitant shoreline erosion. Therefore, it should protect the shoreline from strong wave action and shoreline erosion
Socio-economic value of reef ecosystems	The recovery of reef's ecological functions, goods, benefits, and services should lead to increasing its net productivity and socio-economic value
Community revitalization	A healthy reef provides multiple benefits for local base communities and become instrumental in revitalizing local economies and societies, particularly, in small island scenarios
Food security & sovereignty	A rehabilitated reef will also recover its ability to produce fish protein. Therefore, increased fish biomass will contribute to increasing food security and sovereignty
Goods, benefits and services	Healthy recovered reefs will increase its multiple benefits to humans (e.g., production of food and natural compounds of bio-medical importance, natural breakwater, recreation, and tourism activities). This is fundamental for recovering the economy of small islands
Business opportunities	Successful coral reef rehabilitation has triggered a dramatic increase in low-impact tourism activities in Culebra Island with an informally estimated impact of at least $10 million USD annually. This project will contribute to recover other coral reef habitats, further representing new business opportunities and serving as a model for other locations in PR and the rest of the Caribbean
Recreational opportunities	Rehabilitated reefs and enhanced fish communities also become highly attractive for tourists, snorkelers, and SCUBA divers. This creates multiple new opportunities for the development of recreational activities
Sustainable tourism	Coral reef rehabilitation creates the basis for the development of small island sustainable tourism practices. In this sense, the academia and NGOs will have the unique opportunity to also become leaders in the development of environmentally and socio-economically sustainable activities for small islands
Carbon sequestration and offsetting	Exponentially increasing coral growth lead to an exponential increase in atmospheric carbon dioxide (CO_2) sequestration in the form of calcium carbonate ($CaCO_3$) precipitation during coral calcification. This creates the unique opportunity for developing a carbon offsetting business through low-tech coral farming and reef rehabilitation
Property values	Healthy thriving coral reefs adjacent to the shoreline help to increase adjacent properties values (e.g., landscape, shoreline erosion protection, source of recreation, and food protein)
Stakeholder livelihoods	Healthy reefs help to maintain sustainable livelihoods of local community residents by becoming a potentially sustainable source of food and revenue
People's security, happiness, and wellbeing	Increased livelihood, business, and recreation opportunities for local communities contribute for sustaining their quality of life, security, happiness, and wellbeing

Table 5. Summary of return of investment and added values of coral farming and reef rehabilitation projects.

But in summary, coral farming and reef rehabilitation have provided an important return of investment as well as multiple added values listed in **Table 5**. Basically, it has provided several important local benefits, including the basis for expanding the spatial scale of a sustainable, ecosystem-based model aimed at the recovery of coral reef's ecological functions and services. It has also fostered an improved integration and participation of community-based organizations, the academia, and government agencies to improve opportunities for community-based outreach, hands-on education, technical training, and empowerment. It has also contributed baseline information to support the development and implementation of a public policy in the Commonwealth of Puerto Rico for the conservation of marine biodiversity and the rehabilitation of coral reefs ecosystem resilience, functions, benefits, goods, and services.

In the long term, coral reef rehabilitation is a win-win for all local stakeholder sectors. For local managers, projects can enhance the public presence of leading community-based NGOs and the academia, can contribute to increase the number of trained and educated professionals and stakeholders, foster empowered collaborative management, advance the implementation of no-take MPAs, and habitat conservation goals, and can provide timely information for resource managers and decision-makers. Projects can also provide fundamental baseline information regarding factors such as coral reproduction and growth, fish productivity, connectivity, and coastal resilience. Reef rehabilitation strategies can also contribute to enhance local ecosystems resistance to disturbance, can contribute to buffer wave action, and in the long-term, shoreline erosion associated to sea level rise. Coral reef rehabilitation can also foster a myriad of socio-economic benefits such as increasing the socio-economic value of reef ecosystems; triggering community livelihood revitalization; recovering food security and sovereignty, goods, benefits, and services; fomenting the creation of business and recreational opportunities and the development of sustainable tourism practices; fomenting carbon sequestration and offsetting; and improving property values, multi-stakeholder livelihoods, and people's security, happiness, and wellbeing. Most of these impacts have never been addressed in the literature as they often fall outside the scope of most research and conservation grants, which fail to address multi-disciplinary and social-ecological components of coral reef restoration.

4. Lessons learned from maintenance and data collection

4.1. Maintenance

Regular maintenance of coral farms, and often of out-planted colonies, at least on their initial stages, is a critical process for the success of any project. Such activities can be easily coupled with regular monitoring of corals in farms and of out-planted colonies. Maintenance efforts should have the following objectives:

1. *Sustain health and survival of coral colonies*. This requires regular visits (e.g., depending on the coral farming method, location, trophic condition of the site, herbivory level, etc.), from monthly to at least 3-month interval. However, it is highly recommended to visit and inspect coral farms at least not later than 1 week after coral farming set up and to address any potential structural failure and any possible adverse impact of coral fragment mishandling

and/or transportation stress effect. If possible, corals should be revisited 2 weeks after transplanting. Then, they could be visited after a month, and then at 3-month interval, though this can vary depending on the method, distance from the shore, difficulty of access, etc. This will allow the frequent manual removal of algae, fouling, and opportunistic taxa (e.g., sponges, mat tunicates, hydroids, fire coral) that can potentially smother and/or overgrow coral fragments in farms. This will also allow to identify and remove injured or diseased colonies to prevent potential transmission to other healthy colonies.

2. *Repair potential mechanical damages on coral farming units*. Regular maintenance visits will allow to repair any potential mechanical failure of coral farming units as a result of strong wave action, storm impacts, or damages inflicted by human activities such as boating, anchoring, fishing gear, snorkelers, and recreationists.

3. *Allow qualitative and quantitative documentation of colony survival and growth*. The combination of regular maintenance and monitoring can allow regular qualitative (e.g., photography, video) and quantitative assessments of colony survival, growth, and health conditions.

4.2. Monitoring of coral farms

4.2.1. High survival of coral fragments in nurseries

An important goal would be to achieve a high percent survival (>80%) for coral fragments within the nursery, excluding stochastic events such as fragmentation by storm swells, disease outbreaks, massive bleaching, anchoring, fishing gear entanglement, or snorkeler/diver impacts. Percent colony survival rate should be quantified from the entire population on each farming unit, as well as assessing colony condition and source of mortality, if present (e.g., fragmentation, predation, disease, bleaching, etc.) in a representative sample of fragments. If different genetic clones are being grown, then information should be addressed for each specific clone with an appropriate replicate number of samples per clone.

4.2.2. High productivity and growth of coral fragments in nurseries

Coral fragment growth data, in combination with percent survival rate, are the most straightforward approach to address coral farming productivity success. Basic growth data can include high-resolution fragment's skeletal extension rate, total linear extension, branch abundance, branchiness index (number of harvestable branches above any given minimum size, say 10 cm), by addressing colony diameter or volume or by calculating weight of calcium carbonate produced ($CaCO_3$), either by direct measurements through buoyant weight methods or by geometric estimations. Growth data could be highly variable, depending on sampling size. Therefore, care must be taken to sample a representative number of fragments to minimize variance to achieve a precision >0.80. Depending on the scientific questions addressed and the specific needs of each project and coral species, sampling frequency could be variable, monthly, bi-monthly, seasonal or bi-annual. Sampling can also address colonies from different sources or genetic clones, different generations, and from different size categories. However, it must be noted that if sampling frequency is too low (say, 6-month interval), impacts associated to seasonal variability, pulse events (e.g., rainfall, runoff), predation, disease outbreaks, sea surface warming, or other ecological surprises can be overlooked and not appropriately addressed, therefore, missing critical timely information for managers to understand population dynamics.

High-resolution coral survival and growth data are also critical for parameterizing demographic models and addressing questions of demographic dynamics. However, to gather a basic understanding of coral survival and growth, a basic assessment of coral fragment sizes at the beginning of the project and at any given time later (e.g., 6 months, a year), standardized to initial size, will be enough to address productivity. Productivity will be calculated as annual growth/initial fragment size. Regardless of the approaches taken, it would be important to keep data from different sources/genotypes/generations separate.

5. Lessons learned from out-planting

5.1. Siting of out-planting

The selection of out-plants siting is paramount. The most important elements to consider are to conduct a prior evaluation of environmental history of the potential recipient sites. Is the area too close to urban centers? Are there any adjacent known sewage or storm water outfalls? Any adjacent river outlet? Is there heavy sediment resuspension from boating activities or wave action? Is it too shallow and the area is exposed to constant sea surface warm spells? Is the area highly frequented by snorkelers and trampling activities? Is it impacted by excessive fishing pressure? Is there any evidence of sediment bedload impacts (horizontal sediment displacement)? Is there any lack of juvenile coral colonies? Are there any wild surviving remnants of the targeted coral species? Are there too many standing dead colonies of the targeted coral species and no evidence of sexual or fragment recruitment? These are only a few important elements that must be taken into consideration when planning site selection for out-planting. But, the final selection of the out-planting site should be based on the following standard criteria:

1. Hard bottom substrate free of sediment bedload (=horizontal sediment transport) preferably exposed to moderate water circulation.
2. No observation of fire corals (*Millepora* spp.), sponges, or harmful algae in the vicinity of each out-planted point that could hamper coral colony survival and growth.
3. Select areas known to have previously supported the targeted coral species and that currently have adequate water quality (e.g., adequate transparency, low sedimentation input, no direct sewage effluents, far from river outlets).
4. If possible, select areas with high benthic topographic relief.
5. Avoid areas with high density of coral predators (e.g., corallivore gastropods, fireworms).
6. Avoid areas exposed to significant recurrent runoff effects.

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7. Avoid coral out-planting in direct contact with other corals.

8. Prior to coral out-planting, scrap off the selected sites with a wire brush to remove any algal turf or minor sediment deposits, if any.

9. If out-planting massive corals, select reef outcrops for out-planting. If there is moderate-to-high wave energy or moderate-to-strong surface current conditions at the pre-selected recipient site, various masonry nails should be driven to the substrate as anchors. Then, a dense cement/sand/lime mixture should be placed over the cleaned area among each nail patch. The puck should be buried and secured in the cement, leaving the coral over the substrate.

5.2. Out-planting spatial design

Out-planting spatial design is fundamental for project success and for achieving specific coral reef conservation and rehabilitation goals. Out-planted coral density and spatial configuration can play a critical role in the formation of Acroporid coral thickets, although coral density may play an adverse role in coral survival and growth [60]. But demographic evidence from ongoing studies in Puerto Rico have not shown such trend. In contrast, locality and environmental conditions seem to be more critical factors than species [86] or density (Hernández-Delgado, unpublished data) in affecting out-planted coral survival rates. Increasing out-planted staghorn coral (*A. cervicornis*) (e.g., 1–4 colonies/m^2) can lead to faster recovery of fish assemblages than reefs with lower density (say, 1 colony per 4 m^2) or in control sites without out-plants (Hernández-Delgado, in review). If the objective of coral out-planting is to help rebuild over-exploited fish assemblages, then appropriate spatial designs are key to success. The faster a coral thicket can be formed the faster juvenile fish assemblages can re-establish. A key goal identified by NOAA was for the recovery of *A. cervicornis* populations when "*thickets are present throughout approximately 5 percent of consolidated reef habitat in 5 to 20 m water depth within the forereef zone. Thickets are defined as either a) colonies ≥0.5 m diameter in size at a density of 1 colony per m^2 or b) live staghorn coral benthic cover of approximately 25 percent*" [87]. Achieving such parameters will be dependent upon spatial design. Aspects such as natural reef spatial configuration, depth, wave exposure, presence of special features such as rocky outcrops, spur, and groove systems, aggregated reef patch density, etc. can influence spatial configuration. But as a general rule, depending on coral species, objective of the project and harvested coral abundance spatial configuration can be modified accordingly. In general, if the goal is to rehabilitate local fish assemblages, probably a mosaic of small-to-moderate restored thickets (e.g., 16, 25, 50, 100 m^2 per thicket, with densities of 1–2 colonies/m^2) can be constructed. But if the goal is to provide a long-term buffer against wave action and shoreline erosion, probably parallel lineal configurations of elkhorn coral (*A. palmata*) patches can be constructed along shallow depth contours, from the reef front to the back reefs (e.g., multiple patches 10 × 3 m, 20 × 3 m, 50 × 3 m). Or in such cases, restoration can follow natural existing outcrops contours and configurations. The take home message is to bear in mind what is the specific goal of the project and plan ahead the spatial arrange of corals in order to have an estimate of short- and long-term coral production goals.

5.3. Strategies for out-planting

Coral out-planting requires a thoroughly planned strategy to increase the probability of success. These include several categories. First, transportation needs to be appropriately planned. If harvested corals will be obtained from a local or nearby location (e.g., <1 h transportation), fragments can be transported even under subaerial exposure. However, care must be taken that corals remain humid, well oxygenated, and away from direct sunlight to prevent heat shock stress, possible bleaching, and mortality. But if corals will be transported from farther distances (e.g., 1–2 h or more), then corals must remain submerged, with battery-powered water pump, aerator, and chiller. This has proven a successful method for transporting harvested staghorn coral (*A. cervicornis*) over distances of 150 miles and over 10:30 h of transporting.

Timing of coral out-planting is also an important element to consider. Warmer months (early summer to late fall) must be avoided. At least, across the wider Caribbean region, the warmest period (June to November) coincides with the Atlantic hurricane season. Out-planting during higher sea surface temperature can create higher physiological stress to corals due to higher temperatures in combination with often higher dissolved nutrient concentrations associated to heavy rainfall and nutrient-loaded runoff impacts. These conditions also often foster increased macroalgal and cyanobacterial blooms in many locations, which could further harm recently out-planted colonies. In addition, corals undergo the final stages of gametogenesis during the summer months, therefore, adding extra stress to out-plants.

Finally, the selected strategy will largely have to do with project's goals and objectives. Therefore, components, such as coral size, number of colonies, spatial configuration, and genetic diversity, are important elements to take into consideration for future success.

5.4. Establish restoration benchmarks

Establishing quantitative benchmarks is a key element of any coral reef restoration project. This would imply defining a clear goal, often achievable within 1 year, but larger temporal scales must also be considered (say, 3, 5, 10 year goals). As a minimum, this would include benchmarks for the number of surviving out-planted fragments and for growth rates. Benchmarks would largely depend on the goal of the project. If a goal is limited to replenishing a depleted coral species at any given location or set of locations, then survival and growth rates would provide enough information to address success. For instance, if a 70% colony survival rate is established as a benchmark for out-planted corals, then a survival rate >80% would be considered a success and no actions or improvements would be necessary. If colony survival ranges say between 70 and 80%, caution should be taken and some adjustments should be made to ensure improved success in future efforts. But if colony survival falls below 70%, then action must be rapidly taken to improve methods, spatial design, or site selection.

However, if goals include enhancing ecological connectivity among adjacent reefs, then additional metrics would have to include addressing coral recruitment rates for the out-planted species and genetic connectivity. Also, if the goals include the ecological rehabilitation of reef's functions, then metrics regarding fish community structure, sea urchin populations, and/or herbivory rates would have to be included. The most important aspect of setting benchmarks is to keep in mind that experimental data from the restoration project must be compared to any given "control" or wild site. A wild site would be an ideal habitat with wild colonies of the same restored species, or a site with similar ecological/environmental conditions, but without the restoration intervention. An alternative would be to establish comparisons with different methods, among different locations, and/or to compare restoration performance metrics to those available in the literature from similar projects and from wild sites.

5.5. Data collection

5.5.1. High survival rates of out-planted corals

The survival rate of out-planted coral fragments would be expected to exceed 70% after 1 year in the absence of stochastic events (e.g., hurricanes, winter swells, extreme rainfall and runoff, massive coral bleaching, disease outbreaks, or other ecological surprises). It would be important to keep close track of mortality sources. Additional factors, such as predation, out-competition, disease, sediment bedload, turbidity, and changes in water quality, may play a critical role affecting colony survival and growth. This could vary from location to location, among seasons, and with stochastic disturbances. Percent survival rate should be addressed during each site visit. Also, if known, mortality sources should be documented. If too many colonies are out-planted, then a representative sample should be monitored. If possible, source/genotype/generation data should be kept separate.

5.5.2. High productivity and growth of out-planted corals

Similar to productivity and growth of nurseries, as a minimum, initial and final productivity data for out-planted colonies must be collected to set a benchmark range of coral colony parameters. Parameters addressed, as well as sampling size and frequency, would vary depending on the research questions and project's goals. However, sampling approaches would be similar to those outlined under Section 4.2.2. If possible, it would also be important to keep data from different sources/genotypes/generations separate.

6. Additional recommendations and needs for best management practices

There are other important elements to consider regarding the needs for best management practices (BMPs) for low-tech coral farming and reef rehabilitation. First, there is a need to improve the ability to demonstrate and communicate the socio-economic value and utility of coral reef rehabilitation in providing substantial ecosystem services (e.g., coastal protection, fisheries enhancement, resilience recovery, enhanced revenues from tourism, etc.) to local and state governing bodies, as well as the private sector. This will support decision-making processes on government institutions (across national, regional, local, municipal scales), as well as on cross-sectorial scales, and even on base-community level. This could be important to potentially unlock new funding avenues.

Secondly, there is a need to significantly increase the efficiency and scale of coral restoration to achieve the overall goal of establishing self-sustaining, sexually reproductive populations, and to enhance/restore genetic and ecological connectivity. Sexual reproduction is important to recover coral reef from crisis as it involves the evolutionary mechanisms, such as genetic recombination, that will enable adaptation to the future conditions that corals will face in the context of climate change. There is an implicit need to optimize current coral propagation techniques, including larval propagation, to improve out-planted coral colony survival rates and the efficiency of out-planting asexually derived coral fragments, a need to develop more efficient strategies to accelerate coral growth, and a need to determine the size and density of out-plants for a given coral species to rapidly reach the development of a functional thicket. Also, it would be central to improve genetic variability during out-planting, enabling long-term ecological adaptation to changing climate and environmental conditions and improving population resilience.

There is also a need to develop and implement standardized monitoring guidelines that cover various levels of information (e.g., coral skeletal dynamics, colony conditions, demographic dynamics, spatial extent of live coral cover, thicket development dynamics, genetics, ecosystem functioning). Long-term monitoring must also address different organizational scales, from individual coral colonies to ecosystem processes. Sharing data among practitioners across local, regional, and global scales is central to facilitate understanding of spatio-temporal variability of ecosystem status. Also, fostering inter- and trans-disciplinary dialog among practitioners, scientists, managers, base community volunteers, and other cross-sectorial stakeholders is fundamental, particularly to share lessons learned. There are also fundamental tools to better guide future development of coral reef rehabilitation projects, including: a) Cost-benefit analyses to improve investments in projects; b) Risk analyses to improve siting decision-making; c) the integration of cell automata models to address thicket development potential under different environmental scenarios; d) The coupling of numerical wave models with demographic and spatial heterogeneity models to project wave buffering impacts with reef rehabilitation; and e) the integration of genetic models aimed at the long-term increase of genetic diversity. This would allow prioritizing potential restoration candidate locations, funding allocation, research agendas, and developing targeted strategies for long-term coral persistence in a changing world.

7. Conclusions and recommendations

Low-tech coral farming and reef rehabilitation have become important community-based tools, particularly across multiple small island nations, to foster enhanced non-governmental participation in coral reef management. At least in the wider Caribbean region, these strategies have been successfully implemented to recover depleted coral populations, mostly of

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fast-growing, but increasingly rare, staghorn (*A. cervicornis*) and elkhorn coral (*A. palmata*). They have also been used with relative success, though with limited documentation, to recover depleted fish assemblages. Indirectly, coral reef rehabilitation has also resulted in enhanced benthic spatial heterogeneity, in providing multiple new microhabitat for fish and invertebrate species; has contributed to the recovery of coastal resilience, increasing the protection of shorelines against erosion; and has fostered an increased interest of the tourism sector as an enhanced attraction for visitors and recreationists. But in order to sustainably maintain such benefits, it would be important to pay attention to several metrics and/or components to ensure success.

First, it is important that there are no negative effects of collections from wild donor colonies. There should be no partial or total parental colony mortality, in comparison to adjacent control colonies, and collection of coral fragments should never exceed 15% of the parental colony volume. There should not be reduced growth observed in donor colonies either due directly to fragmentation, and parental colonies should show rapid tissue repair and skeletal regrowth (usually within less than a month). In addition, there should be high percent survival of nursery fragments within the first 1–2 years (>80% survival rate), with the exception of stochastic events such as hurricanes, winter swells, cold water events, disease outbreaks, severe bleaching, etc. If different genotypes are being tested, separate data from different genotypes must be assessed. It would also be important to address specific causes and time of mortality.

Another important component that must be thoroughly addressed is high growth and/or productivity of nursery-grown fragments. This should be calculated as total annual growth/initial fragment size, thus providing a standardized measure of productivity relative to the initial fragment size and helping to reduce some of the variability associated to variations in the initial size of fragments. This would be important for addressing differences among size categories and parameterizing demographic models. It could also allow testing for differences among sites, depth zones, treatments (e.g., along environmental stress gradients, MPAs vs. control non-MPA sites, etc.), and season. It would be difficult, however, to establish a baseline or a standardized range of parameter values due to high latitudinal, longitudinal, site, depth, environmental, genetic, fragment size, and seasonal variability. There can also be substantial variability associated to the use of different methods, even within the same sites, depth zones, and environmental regimes [79]. Therefore, each country, biogeographic zone, or individual project should establish its own monitoring strategies to establish their own baselines. It would also be important to provide frequent maintenance to coral farming units. Measures need to be taken to periodically address colony survival rates, address the physical structure of farming units, remove predators, remove algae or nuisance fouling taxa, and move the nursery to deeper waters in case of storms or hurricanes to improve productivity or projects. A final important metric that should be strongly enforced is to ensure a high survival (>70%) and high productivity of nursery-reared out-planted corals in the absence of stochastic events. This should be achieved through permanently tagging selected, representative out-planted fragments, and through a regular permanent monitoring program. This approach is fundamental for assessing demographic dynamics.

There are also important take home messages to foster increased success of low-tech coral farming. The first is the need to secure sustained, recurrent funding. This may allow to secure a continued input of harvested corals to reef rehabilitation projects, which may allow expanding the spatial scale of projects. Increased spatial scales is a second concern, with the particular aim of fostering enhanced ecological benefits, such as enhancing essential fish habitats, restoring juvenile fish nursery grounds, and recovering ecosystem and coastal resilience. In addition, there is a need to incorporate demographic modeling to coral reef rehabilitation projects. This may allow to improve the ability to address vital population dynamics and project population fate under variable environmental and climate change-related scenarios. Coral farming and reef rehabilitation have also shown to be a successful fishery management tool on local scales. Therefore, it can be used to integrate local communities and fisher villages to fishery management strategies. Under increased spatial scales, it should also become a tool to manage coral and fish connectivity, at least across ecological spatial scales. This would further foster the implementation of a participatory model to foster improved coastal resilience, MPA, and coastal resilience management.

Finally, it would be fundamental to foster the creation of functional partnerships among base communities, NGOs, the academia, government institutions, and the private sector. This would allow the development of stronger networks to improve volunteerism, outreach and education, and improve the possibility of securing continuous funding support. In a time of projected increases in climate change and sea level rise, low-tech coral farming and reef rehabilitation must be fortified and expanded across multiple localities. Only through the integration of multiple sectors of society, the goal of expanding the spatial scale and full community integration can be achieved. In a time of significant projected climate change impacts and sea level rise, improving the scale of coral farming and reef rehabilitation has become a critical tool for coral reef conservation. But multiple roadblocks must still be overcome. The future of coral reef productivity and its attractiveness for tourism can be sustained through proper participatory management for the enjoyment of future generations.

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