# Multi-disciplinary Lessons Learned from Low-Tech Coral Farming and Reef Rehabilitation: II. Coral Demography and Social-Ecological Benefits Provisional chapter Mult....

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Chapter 11

# Multi-disciplinary Lessons Learned from Low-Tech Coral Farming and Reef Rehabilitation: II. Coral Demography and Social-Ecological Benefits

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**Abstract**

Low-tech coral farming and reef rehabilitation have become important tools to foster community-based participation in the management of coastal social-ecological systems. Lessons learned from coral demographic dynamics, ecosystem-level benefits, and sociological dynamics achieved in Culebra Island, Puerto Rico, are discussed. Important gaps regarding social-ecological interactions are also addressed. Coral reef rehabilitation efforts must be adaptive and focused on maximizing resilience as a long-term goal, with emphasis on managing non-linear dynamics, thresholds, environmental and climate uncertainty, and ecological surprises. In this context, coral demographic modelling becomes fundamental to address, not only ecological, but also sociological concerns. Only through sustained support and input of harvested corals restored populations, and by increasing the spatial scale of reef rehabilitation, restored populations can remain viable and grow under present and projected environmental and climate conditions. Understanding sociological dynamics, learning from others experiences, integrating visioning and scenario building, leadership building, multi-sectorial agents and actor groups, and strengthening cross-sectorial social networking are necessary adaptive approaches to cope with future environmental and climate changes, and are an integral part of reef rehabilitation. The combined benefits to social-ecological systems are multiple. With proper planning, design, funding, local support, and implementation, these can have long-lasting impacts in restoring coastal resilience.

**Keywords:** coral farming, coral reefs, ecological rehabilitation, lessons learned, Puerto Rico, Caribbean Sea, reef fish communities, social-ecological systems

# 1. Introduction

## 1.1. Coral reef decline and the erosion of social-ecological systems

Coral reefs have largely lost species diversity, ecological functions, ecosystem resilience, and socio-economic benefits across regional to global scales over the last four to decades. These have resulted from a combination of impacts from extreme natural hazards (e.g., hurricanes and tsunamis), from multiple localized human drivers [1–5], and from climate change [6, 7]. This has often resulted in a largely reduced ability to recover from acute, recurrent or chronic disturbances, compromising their capacity to sustain biodiversity, ecosystem services, local economies, and threatening the sustainability and resilience of social-ecological systems [8]. This is a particular concern for low-lying coastal communities and for small tropical islands, which often have very significant governance limitations, as well as limited socio-economic capital to cope with disasters. In this context, coral farming and reef rehabilitation efforts are becoming increasingly important strategies to incorporate in the coastal management toolbox, but which have never yet been implemented as strategies to address issues related to restoring the resilience of coastal social-ecological systems.

Ecological resilience can be defined as the buffering capacity or the "*ability of a system to absorb changes of state variables, driving variables, and parameters, and still persist*" [9]. In this context, resilience is a property of a system, and persistence or probability of extinction can be the result, depending on the system's trajectory and stability. Stability is the ability of a system to return to an equilibrium state after any disturbance [9]. The more rapidly a system returns, and with the least fluctuations, the more stable it is. However, under present rapidly declining of coastal social-ecological systems, mostly coral reefs, stability has also declined, so the ability of systems to absorb and recover from disturbance. Therefore, any long-term trend resulting in the net erosion of the stability of a social-ecological system can threaten its long-term resilience, and may result in a combined loss in the ecological (e.g., biodiversity, functional redundancy, ecosystem services) and social persistence (e.g., local economy, livelihoods). The geographical isolation of small islands, in combination with historical socioeconomic and political constraints, increasing threats by sea level rise (SLR) and climate change, can often magnify vulnerability to such impacts [8], and may result in a net erosion of social resilience.

Social resilience was defined as "*the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change*" [10]. Social resilience is a fundamental characteristic of ecosystems which has still remained poorly addressed, but which is critical to maintain ecosystems functions and services in the face of disturbance, including extreme weather events (e.g., hurricanes), natural hazards (e.g., tsunamis), chronic human-driven environmental degradation, SLR, and climate change. There is a clear link between social and ecological resilience, particularly for coastal communities, and small island nations that are largely or fully dependent on ecological and environmental resources for their economy and local livelihoods.

Exposure and sensitivity to hazards of coastal social-ecological systems are largely dependent on the ecological status and vulnerability to disturbance of coral reefs. Reducing exposure and sensitivity requires maintenance and enhancement of reef ecosystems functions through sustainable management and use [11]. In this context, coral farming and reef rehabilitation have become fundamental management tools to engage base communities in sustainable social-ecological systems management. It would also be important to maintain the local memory of resource use, and foster the development of learning processes for responding to environmental feedback and social cohesion [11]. Therefore, base-community engagement in coral farming and reef restoration must also be coupled with hands-on education and training, with the aim of achieving long-term local empowerment, stewardship and support. The other critical element of vulnerability of coastal social-ecological systems is adaptive capacity. Sustaining coastal social-ecological systems requires the recovery of biodiversity in ecological systems, and expanding the diversity of the local economic livelihood portfolio. Both alternatives can be readily achieved through low-tech, community-based coral farming and reef rehabilitation. However, an important challenge is the need to empower local to national governance structures and social capital, bridging gaps among local communications, academia, private organizations, and government for integrative responses, and building horizontal, cross-sectorial networks in society for social learning.

Nevertheless, bridging the gap between decision-makers, natural resource managers, empirical academic research in regards to coral farming and reef rehabilitation, and the socio-economic component of these efforts have remained poorly explored, and still remains as a top challenge to overcome across local, national and regional scales. Understanding the critical value of integrating question-driven research in reef rehabilitation efforts is paramount to advance knowledge and to communicate that technical knowledge to base communities and local stakeholders. One such component is to integrate coral demographic dynamics and modeling into active reef rehabilitation efforts. But also, the integration of lessons learned from sociological dynamics in regards to coral farming and reef rehabilitation is a highly necessary added value that should contribute to improve future projects.

Therefore, lessons learned regarding the need to understand the mechanisms of improving the management of both, the ecological and the social components of coastal tropical systems is essential to improve management success, and to foster an improved education, stewardship and participation of base communities in coastal management. 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.

### 1.2. Goals and objectives

The goal of this chapter is to briefly update the state of knowledge regarding applied coral demographic dynamics to low-tech coral farming and reef rehabilitation efforts, mostly using case studies of restored populations of endangered Staghorn coral, *Acropora cervicornis*. Important elements associated with coral demographic and oceanographic modeling have also been addressed as decision-making tools regarding its application to large-scale restoration efforts. Also, sociological lessons learned, which are often overlooked, have been discussed, including: volunteer work, team assemblage, building local support and stewardship, and socio-economic benefits. Most of the discussed examples are derived from lessons learned through the *Community-Based Coral Aquaculture and Reef Rehabilitation Program* established in 2003 in Culebra Island, Puerto Rico, by non-governmental organization (NGO) Sociedad Ambiente Marino.

## 2. Lessons learned from coral demographic dynamics

### 2.1. Coral demographic modeling in reef rehabilitation

Whether any given population increases, decreases, remain stable or face extinction depends upon the rates at which an individual grows, die, and reproduce. Most conservation and management-oriented efforts are intended to increase population growth rate of the targeted species until reaching a growing or stable state and identifying which vital stage(s) is (are) essential for the conservation and management of an endangered or threatened species. Demographic-based population models are convenient and efficient tools that not only allow to perform population viability analyses, but also allow a detailed examination of the relationship between demographic traits/rates and population growth rate ($\lambda$). One of the strengths of demographic-based population models is that they take into consideration the influence of the developmental stage (age, size, and stage) on individual's vital rates and link it to the population level [12]. At the same time, demographic models can be subjected to prospective (e.g., sensitivity and elasticity) and retrospectives (Life Table Response Experiment) analyses to examine the relative importance of each of the vital rates on $\lambda$ and to investigate the effects of physical and biological disturbances on the population dynamics of a target species [13, 14]. Prospective analyses (e.g., sensitivity and elasticity) looks at how $\lambda$ would respond when a particular life cycle transition is perturbed [12]. Life Table Response Experiment analysis, on the other hand, provides information on how much variation in a particular life cycle transition contribute to the observed differences in $\lambda$ between treatments (e.g., restoration vs. no restoration). Another advantage is that models can be manipulated to assess how any given population would respond to changes in any of the vital rates (e.g., reproductive failure, mass mortality) or any given restoration initiative; thereby providing the basis for the design of future restoration and conservation projects under variable environmental conditions, climate change-related scenarios, etc.

In the last couple of decades, demographic-based population models (e.g., population matrix models and integrated population models) have become an essential part of conservation studies [15]. However, few coral biologists have applied demographic-based population models to answer specific conservation questions (but see [16–19]). Vardi et al. [17] and Mercado-Molina et al. [18] used size-based population matrix models have been used to describe the demography and population dynamics of threatened coral species *Acropora palmata* [19] and *A. cervicornis*, respectively [18]. They found that the demographic transition that contributes the most to local $\lambda$ is the survival of large colonies. Thereby, providing evidence that restoration and conservations efforts of these corals species should be focused on enhancing the probability of large colonies to survive. Mercado-Molina et al. [20, 21] found that both growth and branching rates of *A. cervicornis* increase with size. Therefore, positive contribution of large colonies to λ, at least for *A. cervicornis*, can be partly explained by (1) a rapid growth that can allow the colony to reach a refuge size in which mortality associated with diseases, predation, and bleaching can be considerably reduced; and (2) an increase in the number of branches with the potential to be detached from the parental colony and become established as an independent colony, contributing to faster formation of thickets.

Demographic transitions and population growth rates of *A. palmata* were relatively stable over a 6-year study period, except for a hurricane year which naturally caused a significant decline in population growth rate [17]. In contrast, spatiotemporal differences both in the transitions rates and λ of *A. cervicornis* were observed [18]. These contrasting results indicate that even when *A. cervicornis* and *A. palmata* share similar life cycles, their demography varies considerably. Therefore, conservation and restoration activities should be designed at the species-specific level whenever possible, with separate specific goals and objectives. The spatiotemporal differences in demographic transitions displayed by *A. cervicornis* [18] also suggest that restoration efforts should be partitioned among several locations rather than allocating all the resources into one site. This action will enhance the persistence of the species if localized extirpation occurs due to spatial variability.

### 2.2. Modeling as decision-making tools

The current limitation in human, technical, and economic resources, together with multiple frequent logistical constraints, have made coral conservation a difficult task, especially in small islands, and when long-term studies are not feasible or available. The most basic demographic parameter that can be obtained using demographic modeling is the intrinsic population growth rates, lambda (λ). When $\lambda = 1$, the population is stable, if $\lambda < 1$ the population is decreasing in size, and when $\lambda > 1$ then the population is growing positively. Thus, by directly estimating λ practitioners can determine whether a given population needs management attention. Using population models to project population size over time is one of the most attractive alternatives to understand how any given wild or restored population would behave under different restoration and conservations scenarios (see [17, 18, 20]). Studies by Mercado et al. [18, 20] coincided in that without human intervention (e.g., coral out-planting) local *A. cervicornis* population growth in the wild is not granted. However, contrary to the *A. palmata* populations [17], which are expected to remain stable (no significant growth, no significant decline) over time, *A. cervicornis* populations can go extinct in less than two decades [18, 20]. Such contrasting population trajectories may be the result of *A. cervicornis* being more susceptible to low and moderate environmental changes [18, 22]. Therefore, *A. cervicornis* is more at risk of localized extinction than it is congeneric. Indeed, *A. cervicornis* colonies are much more ephemeral than *A. palmata* (e.g., they suffer a high rate of complete mortality and complete colony dislocation) [22]. This implies that continuous low-tech coral farming and out-planting efforts are fundamental to sustain restored populations in the wild.

The initial size of the coral transplant needs to be taken into consideration to assure the success of any restoration project [17, 18]. Both studies concluded that transplanting large colonies will result in higher population growth rates than transplanting small colonies, as many standard coral farming operations do, at least across the Caribbean. However, transplanting large colonies pose some challenges; specifically, regarding the time necessary for a nursery-reared coral fragment to reach the effective transplantation size [18]. However, numerical simulations have demonstrated that increasing the number of small-sized transplants of *A. cervicornis* enhances the probability of population stability [18]. For an initial population size of 150 *A. cervicornis* colonies, transplanting 50–75 fragments ≤100 cm in Total Linear Length (TTL) annually would result in a positive population growth rate.

Population models can also be used to test the effectiveness of different management regimes (e.g., intensity, environmental and climate change scenarios) such as alternating times of out-planting and nonout-planting. So far, only Vardi et al. [17] have published results by taking such approach. They projected *A. palmata* population size under a scenario that alternate 2 years with no out-planting and 5 years in which 1000–3000 colonies are transplanted, followed by an additional 13 years with no out-planting. Under such management design, populations will grow positively over time. Therefore, it can be argued that such management plan is appropriate to assure the persistence of the impacted population. **Figure 1** shows a simulation based on the model developed by Mercado-Molina et al. [18] for two wild populations of *A. cervicornis* in northeastern Puerto Rico, in which the effect of two out-planting scenarios on local population abundance was simulated. The scenarios considered the out-planting of 1000 colonies for two and five consecutive years, respectively. These scenarios were based on the fact that most restoration projects are funded for less than 5 years and for the number of fragments that in our experience can be produced in 1 year in our nursery units. The results indicated that under such out-planting regimes populations would

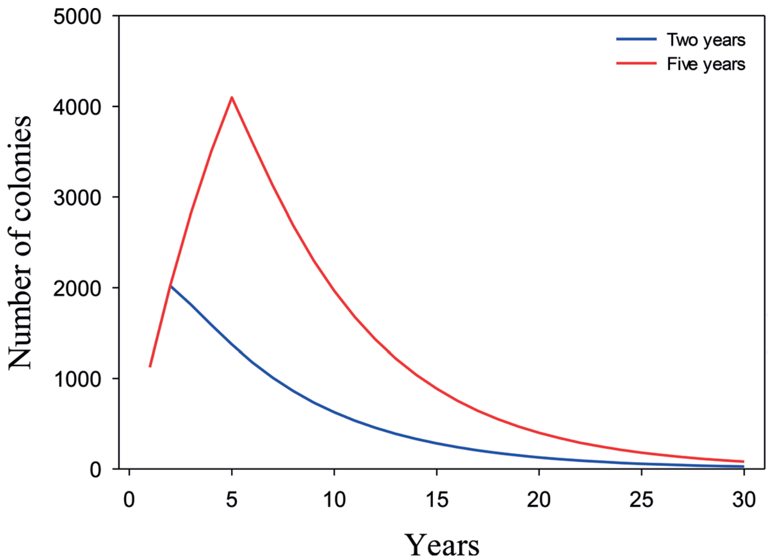


**Figure 1.** Numerical simulation based on the model developed by Mercado-Molina et al. [18] for two wild populations of Staghorn coral (*Acropora cervicornis*) in northeastern Puerto Rico, in which the effect of two out-planting scenarios on local population abundance were assessed.

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not be able to persist over time. This outcome, together with simulations run by Mercado-Molina et al. [18], led us to conclude that restoring populations of *A. cervicornis* by out-planting coral fragments is a feasible strategy, but one that requires sustained human intervention.

### 2.3. Increasing the spatial scale of reef rehabilitation

One of the major limitations of coral reefs restoration is that all projects so far are small in spatial scale, often varying from tens to hundreds of $m^2$, with a limited number of projects ranging between 100 s $m^2$ to less than 1 $km^2$. Increasing the spatial scale of reef rehabilitation is essential, at least for *A. cervicornis*, because its demography varies considerably in time and space. Increasing the spatial scale of population rehabilitation will increase the probability of species persistence. Coral out-plant spatial array is also critical for the formation of thickets. Before the 1980s, *A. cervicornis* used to dominate the seascape of shallow-water reefs by monopolizing vast areas of the substrate [23]. It is necessary to take conservation and/or restoration initiatives directed at re-establishing the large thickets this coral used to form. The *Acropora* Recovery Plan [24] established the development of *A. cervicornis* thickets as a major goal of restoration projects. However, there is still scarce information regarding the demographics and dynamics of thicket formation that could be used as a basis for the design of management strategies. But model thicket formation can use novel approaches such as individual-based dynamical automaton models (IBDA) [25, 26], and use the predictions of the model to determine the number and spatial arrangement of out-plants that will maximize the likelihood of thicket formation, and improve reef restoration strategies and spatial designs.

Increasing the spatial scale is also important for increasing the recovery of fish assemblages and rehabilitating reef processes. However, there is still a significant information gap regarding the role of coral reef restoration on enhancing essential fish habitats and fish assemblages. Fish assemblages are sensitive to the spatial heterogeneity of the benthos [27] and habitat condition [28]. Any disturbance resulting in mass coral mortalities [29], benthic community regime shift [30], and in loss of benthic spatial heterogeneity [31] should adversely affect coral reef fish assemblages. Therefore, management strategies aimed at rehabilitating depleted fish assemblages should include coral out-planting at increasing spatial scales and/or focused on developing habitat mosaics as a mechanism to restore benthic spatial heterogeneity.

Also, increasing coral reef rehabilitation spatial scale is a fundamental step necessary to achieve progress in restoring and managing coastal resilience (e.g., wave buffering, reducing shoreline erosion rates). But fundamental questions associated with coral reef restoration projects at sites, where wave energy reduction is an important design criterion. What is the degree of wave attenuation that can be expected from out-planting Elkhorn coral (*Acropora palmata*) at the selected sites? What factors (how big should colonies be at out-plant, how far apart, thicket size, shape, and spatial arrangement, water depth, local wave climate, etc.) should be considered when designing a coral reef restoration project in order to maximize wave energy dissipation? What are the expected costs for downscaling numerical wave models for different locations? What data should be collected to successfully simulate the performance of the proposed coral restoration activities? What other data on coral health should be collected to better inform the modeling efforts? These are areas which are being currently investigated at the University of Puerto Rico, which should provide new light in regards to the potential application of coral reef restoration as a novel coastal resilience management strategy.

### 2.4. Next steps in coral reef restoration

The next logical steps in coral reef restoration have mostly to do with improving *ex situ* propagation of coral larvae, enhancing the effectiveness of micro-fragmentation techniques to foster a higher number of small colonies and faster initial growth rates of massive coral species, improving the ability to discriminate and propagate different genetic clones, and improving the spatial scale of coral out-planting to achieve faster and functional coral patch or thicket formation. Furthermore, there is a critical need to figure out: (a) how to distribute available funding more fair and evenly, and how to achieve economic auto-sustainability; (b) how to shift the standard institutional short-term, isolated vision of projects to a long-term goal-driven program (c) how to develop some standardized farming, maintenance, and out-planting practices; (d) how to implement standardized integrative metrics of success (e.g., from colony to ecosystem level); (e) how to foster, achieve and support community-based and NGOs participation in these projects; and (f) how to foster the creation of functional partnerships among government institutions, the academia, NGOs, base communities, and other private sectors. But there are still a few limiting components associated with low-tech coral reef restoration efforts that still must be quickly addressed.

#### *2.4.1. Lack of knowledge of Staghorn coral (Acropora cervicornis) branching dynamics*

Despite colony branching dynamics is the basis for *Acropora cervicornis* restoration projects, little is known about branch production of the species. Branching rates in this species growing in nurseries and in colonies out-planted to the reef, respectively, increase with colony size [19, 20, 32]. Thus, growing large-sized colonies in nurseries, as well as those colonies out-planted to the reef, may result in greater number of branches available for a restoration project, increasing the potential coral propagule abundance available for future restoration efforts. At the same time, out-planting large colonies would result in colonies with higher levels of branching complexity in relatively shorter time than transplanting small single-branched fragments, which favor faster thicket formation. It is known that more complex coral colonies promote reef biodiversity [33, 34]. Still missing, however, is information about the intrinsic (i.e., genetics) and extrinsic (i.e., temperature; light) factors that stimulate/limit branch production. Such information is essential, for example, to select the sites for the deployment of nursery units, select the most appropriate sites for restoration, and estimate the number of branches that can be produced for restoration purposes and future natural asexual propagation in the wild.

#### *2.4.2. Increasing the spatial scale of reef rehabilitation*

Increasing the spatial scale of population rehabilitation will increase the probability of species persistence for most corals. Nevertheless, the process of selecting the sites to be restored is not based on empirical data about the demographic performance of targeted corals, but rather on the assumption that the historical or current presence of any given species (e.g., *A. cervicornis*) reflects the appropriate conditions for the development of the species. Also, site selection might often be based on the perceptions that water transparency, deeper environments, or high distance from potential pollution sources represent the most suitable habitat conditions for out-planting. Site selection can be critical for coral restoration success as poor site condition can be detrimental [35]. Even low to moderate differences in local biotic and abiotic conditions can have profound effects on $\lambda$ [12]. Also, preliminary results by Hernández-Delgado (unpub. data) suggest that the abundance and widespread dispersion of invasive red encrusting algae *Ramicrusta textilis* (Rhodophyta, Peyssonneliaceae) is a critical factor affecting the survival and growth of *A. cervicornis*, even under remote conditions and high water transparency. Accordingly, a better criterion of restoration success should be the local population growth rate of *A. cervicornis*, rather than presence/absence of the species.

#### 2.4.3. Most restoration projects are not firmly grounded on quantitative demographic analyses

Because population growth rate is inevitably linked to individuals' survival, growth, and reproduction, effective conservation initiatives require knowledge on how variation in vital rates relate to variations in population growth. Population studies focused on restored populations of *A. cervicornis* have not been firmly grounded on quantitative demographic analyses [19]. Several population studies have estimated rates of colony growth and survival [36–38]. None, however, identified how spatiotemporal variations in outplants survival, growth, and rates of recruitment (e.g., number of outplants) affect $\lambda$ of restored populations. The lack of studies that directly evaluate the population response to demographic variability limits our capacity to develop effective restorations initiatives. Very few studies have attempted to address essential questions such as: How long restored populations would last without human intervention? How many fragments would be necessary to keep populations viable? How often out-planting activities need to be carried out to assure the persistence of the restored populations? Which is the effective colony size of transplantation? The answers to these questions are fundamental for the development and success of restoration activities. And demographic modeling can lead the way to answer them.

#### 2.4.4. Short-term funding: a roadblock to long-term success

Funding is a major factor limiting the development and success of restoration projects. Most of the projects are funded for 1–3 years [39]. This short period of economic support certainly limits the amount of spatiotemporal demographic data that can be used to parameterize population models. Indeed, the low spatiotemporal resolution is one of the main criticisms raised by many researchers against the use of population modeling for conservation purposes. More data is always better; however, "limited" data must not discourage the use of demographic and population modeling as a tool for the development of restoration initiatives. Collecting data for an undetermined amount of time waiting to obtain "robust" demographic data to parameterize any given model might just be too late for a threatened species whose populations are declining very rapidly.

One year of demographic data is the minimum amount necessary to perform a basic population model based on estimates of population growth rates. The demography of many marine clonal/modular organisms has been successfully described using ≤2 year of demographic data [13, 16, 40–44]. The relatively "short time frame" of these studies has not impeded making a significant contribution to our understanding of coral demography. In fact, most of the studies focusing on the demography of corals are short-term (≤4 year). This is not surprising, given the limited resources available to monitor populations of conservation concern. On the other hand, studies considered "long-term" (5> year) have been focused, with the exception of Vardi et al. [17], on massive species such as *Porites astreoides*, *Pseudodiploria strigosa*, and *Orbicella* (*Monstastraea*) *annularis*, which contrary to *Acropora cervicornis*, are characterized by low growth rates and therefore require higher temporal resolution to detect changes in demographic transitions [45, 46].

If the intention is to conduct demographic analyses that take into consideration environmental variability, both in space and time, then at least 2 years of demographic data are necessary. It is well established in the demographic literature that two temporal points (2 years) are sufficient to perform the stochastic analyses (e.g., population viability analysis, stochastic population growth). Morris et al. [47], in their book "A Practical Handbook for Population Viability Analysis (PVA)," stated that *demographic data on a subset of life stages for only 1–2 years*" is sufficient to make a population viability analysis "*profitable*." Fieberg and Ellner [48] recognized that "*[Stochastic matrix] models are typically parameterized using two or more sets of estimated transitions rates between age/size/stage classes*." Likewise, using two annual transitions to perform demographic analyses (e.g., PVA, stochastic population growth) is more suitable [12]. It is important to note, however, that demographic and population models are not crystal balls that predict the future of a population under a certain set of conditions. Nature cannot be replicated, and as such the results of any given model need to be considered as possible population outcomes which should be combined with the best information available to take educated conservation decisions for this species.

#### *2.4.5. Coral reef rehabilitation to restore ecological connectivity*

Depending on the configuration of coral out-planted patches, its spatial distribution and the temporal extension of coral reef rehabilitation efforts it may become a critical tool to manage ecological connectivity among adjacent reef systems. The whole concept has to do with fostering enhanced depleted coral stocks, therefore, increasing local populations' reproductive potential and output. This will allow increased gamete release, reduced gamete waste, reduced Allee effect, and enhanced probabilities of sexual reproduction and recruitment. In theory, this would allow to enhance genetic recombination, improve population fitness, and allow for increased connectivity with downstream reef systems. For this to be successful, understanding local to regional oceanographic dynamics is fundamental. Thus, numerical wave model development, as well understanding often complex surface circulation patterns, is very important as a planning tool to shape future long-term coral reef restoration initiatives. Indirectly, this can also become a very important indirect component of reef fish conservation and restoration management as restored coral reefs can restore benthic spatial heterogeneity and rehabilitate essential fish habitat functions across ecologically connected scales fundamental for reef fish dispersal.

## 3. Lessons learned from fish community dynamics

### 3.1. Impact of community-based reef rehabilitation on fish communities

Coral reef rehabilitation results in increased benthic spatial heterogeneity, which enhances micro-habitats for fish shelter on local scales. Post-larval and juvenile grunts (*Haemulon* spp.) have shown up to 10-fold increase or more in abundance in areas where *Acropora cervicornis* has been out-planted (Hernández-Delgado and Suleimán-Ramos [49]). But also, multiple other taxa show significant increases in fish abundance and biomass. Ongoing studies by Hernández-Delgado have shown that juvenile guilds of multiple families, such as parrotfishes (Scaridae), wrasses (Labridae), damselfishes (Pomacentridae), blue tangs and doctorfishes (Acanthuridae), and predators, such as snappers (Lutjanidae) and groupers (Serranidae) can increase in abundance and biomass, in comparison to adjacent control sites without out-plants, or in comparison to restored sites before out-planting. There is also an increase in fish abundance and biomass with increasing thicket age, comparing 1-, 2-, and 4-year-old patches. Further, areas located within the Canal Luis Peña no-take Natural Reserve showed higher fish density and biomass, in comparison to control sites outside the reserve exposed to fishing. Therefore, preliminary evidence already points out at the emerging role of low-tech community-based coral reef rehabilitation as a highly useful tool to restore and rebuild coral reef-based fisheries.

### 3.2. Impacts on herbivory

Ongoing studies by Hernández-Delgado have also shown increased abundance and biomass of fish and invertebrate herbivore guilds. As mentioned above, parrotfishes (Scaridae) and acanthurids are among the most abundant fish taxa across reef rehabilitation sites, in comparison to areas with no coral out-planting. Further, *Acropora cervicornis* out-planting has resulted in increased abundances of the Long-spine urchin (*Diadema antillarum*). This has resulted in increased herbivory upon macroalgae and algal turf, and in increased percent cover of crustose coralline algae (CCA). Over temporal scales of 5–10 years, this has resulted in higher coral sexual recruitment rates across restored areas.

## 4. Sociological lessons learned

### 4.1. Building local support and stewardship of social-ecological systems

Building local support and stewardship of social-ecological systems is a critical process for achieving success in any community-based marine protected area (MPA) participatory management or co-management effort. Community-based coral farming and reef rehabilitation also requires such support and stewardship. Multiple environmental problems frequently raise concern on residents of coastal communities, and a few highly concerned people assume the community leader role hoping to find solutions. However, at least in Puerto Rico, most base-community members lack the technical and scientific resources to meet the minimum and urgent needs of their community. Therefore, a basic step for successfully achieving solutions is to organize, establish a goal and delineate a functional plan to achieve objectives. But this may often require seeking technical and scientific support from the academia and NGOs. Integrating multiple stakeholders in coral farming and reef rehabilitation efforts is a key for overcoming such obstacles.

Community-based leaders can often provide a fundamental historical background that can provide valuable information to understand and resolve problems. Traditional ecological knowledge has been significant for success in Culebra Island and at Vega Baja, Puerto Rico. Particularly, old fisher folks can provide very detailed information regarding the ecological history of local coral reefs that can help rebuild local environmental history and identify coral reef rehabilitation strategies. In addition, the interaction among base communities, NGOs, the academia, the private sector, and the government can allow and strengthen the development of trust. This is a critical element for achieving successful transparent collaboration in social-ecological systems. Building up such local partnerships will foster building stronger functional networks, with the support and respect from agencies and private institutions. It can also strengthen outreach and educational efforts through a combination of hands-on training activities, workshops, and other methods to generate commitments among the stakeholders who traditionally adopt roles as volunteers as they feel confident and dominate different skills.

Another key element to build local stewardship and support are exchanges and cross-sharing of experiences with sister organizations and base communities to share knowledge, and lessons learned in support of each other's work. Networking, among different sectors, can further allow strengthening communication and sharing of experiences.

### 4.2. Building a volunteer network

Building up a strong and consistent volunteer network is another key to success. This can be achieved through proper organization, direction, well-established goals, and a functional, realistic work plan. There is also a need to integrate educational and hands-on training to develop and strengthen theoretical and technical skills, build stewardship and compromise, assign roles and tasks, etc. Even the difference in personalities and needs can provide a wide range of opportunities for participation. Individuals have different needs, from basic nutrient supplementation, to self-realization. Different needs function as motivation in performing tasks beyond satisfying personal needs. The collective need of volunteers represents the necessity of their environments or communities.

A transparent dialog between volunteers and collaborators can help build up cooperative working links serving different needs for the same adversity. Further, building up large teams of volunteers can help to have always people available for labor-intensive field work, preventing burning out the same group of people. It is therefore important to know about your volunteers, their interests, needs, their chemistry as a group, their personalities, and their strengths and weaknesses.

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### 4.3. Team assemblage

A fundamental step in achieving team success is the selection process of proper members of a coral farming or reef rehabilitation team. Team technical leadership is important to provide direction during planning and field work. Personality issues, individual responses and performance to different specific tasks and roles, and differences in strength and weaknesses are also important elements to consider. Understanding the profile of volunteers, their needs, and the different characters and temperaments can allow making a good distribution of the workforce, avoid conflicts that impede the growth of the organization, as well as the fulfillment of goals and objectives.

### 4.4. How to overcome lack of funding?

Lack of long-term commitment by funding sources can be a major obstacle for advancing project's goals and achieving success. Lack of commitment by government agencies and funding institutions, indifference by private businesses and tourism industry, and the lack of a long-term vision of projects goals can lead to rapid failure. Therefore, the need to engage local community, build stewardship, volunteerism, integration of university students through research and first laboral experience programs, etc., becomes instrumental to buffer limited funding, and to strengthen management of coastal social-ecological systems. Nevertheless, in a time of significant socio-economic constraints, there is a need to explore alternative funding avenues from multiple auto-sustainable economic strategies. These might include alternatives such as: (1) "Adopt a coral" program—aimed at the general public and the private sectors, including options such as: adopting an individual coral, a determined number of colonies, a coral thicket, a reef patch or an entire reef; (2) Develop a "Reef sponsoring program" for private corporations—aimed at developing a sponsoring program that may also have different levels of support; (3) Develop crowd funding strategies through the web—aimed at using the world wide web to develop a cyber-campaign for raising awareness about coral farming, reef conservation and restoration, and for fundraising for any given project, with usually a goal-driven funding limit for a specific project; (4) Establish a system of green taxes—aimed at auto-sustaining natural resource management, including activities such as MPA management, mooring buoy maintenance, patrolling, outreach and education, guided tours, coral farming, and reef rehabilitation, among others. Green taxes can be derived from multiple tourism-based activities such as airplane landing fees, cruiseship taxes, private yacht taxes, SCUBA diving and snorkeling charter boat operations, kayaking, vehicle rental, hotels, etc.; and (5) Establish different sources of funding from different government revenue collection systems—this may include through specific taxes to luxury yachts, vehicles and properties, from liquor and cigarette expenses, from industrial revenues, etc.

Under current local, regional, and global socio-economic decline, it is paramount to develop and implement creative strategies for seeking financial support. But to achieve this, strengthening local organizations, building up strong partnerships with different sectors, and fostering community-based participation are fundamental steps.

### 4.5. How to overcome other roadblocks?

Even successful community-based and academic projects can face multiple roadblocks in their day to day work. Aspects such as permitting bureaucratic processes, access to restoration sites, beach access issues, privatization and roadblocks, conflicts with other uses (e.g., tourism, charter boats, kayaking, fishing, and navigation), lack of prioritization of coral reef rehabilitation by local/national government institutions, lack of local community stewardship and support, indifference by private businesses, etc., can all be deleterious for project's success. If any or at least some of these factors are present in any project there will be a need to improve outreach and educational campaigns to strengthen project's pertinence to local stakeholders and institutions, and to strengthen social-ecological systems resilience. Also, it would be important to build up communication channels with private entities and show the benefits that successful coral farming and reef rehabilitation can bring to their businesses. Achieving such collaborative support would be important to strengthen economic support.

### 4.6. How to overcome uncertainties and change?

Management of uncertainties and change under projected environmental and climate changes constitute a major challenge. For instance, increasing frequency and/or strength of hurricanes fuelled up by increasing sea surface temperature (SST), if combined with weak governance, can result in major crisis. In situations where uncertainties and change are key features of the social-ecological landscape, critical factors for sustainability and rapid recovery are resilience, the capacity to cope with crisis and adapt, and the conservation of sources of innovation and renewal [50]. Such is the case of the impact of extreme weather events and ecological surprises impacting coral farming and reef rehabilitation. However, interventions in social-ecological systems with the aim of altering resilience immediately confront issues of governance. Who decides what should be made resilient to what is a critical question for any reef rehabilitation program. For whom is resilience to be managed, and for what purpose are also two key elements that must be decided during the planning stages of any project, always bearing in mind the long-term goal of managing uncertainties and change.

### 4.7. Socio-economic benefits of coral farming and reef rehabilitation can be offset by lack of governance

A major lesson learned from the Culebra Island coral farming and reef rehabilitation experience has been that the rapid increase in socio-economic benefits from increased nature-based tourism does not always contribute to support social-ecological systems under a weak governance structure. Increasing tourism and business opportunities (e.g., kayaking, shore-based SCUBA/snorkeling, charter vessels, beach swimming, hotel lodging, vehicle rental, bus services, etc.) have resulted in a significant boom in gross revenues for local and external private businesses. This has resulted in increasing alternative job opportunities. But a weak governance structure still allows the leak of revenues from the local community, favoring external businesses, and the total lack of economic support of the local MPA, and local coral farming and reef rehabilitation efforts. Therefore, strengthening governance is a critical step to support the ecological

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and socio-economic recovery of social-ecological systems resilience, stability and persistence, and a mechanism to foster increased local participation and sharing of benefits.

A second important benefit in Culebra Island has been increasing fish densities on rehabilitated reefs, therefore contributing to enhance fishing on adjacent areas, through fish spillover effects. Also, reef rehabilitation has resulted in increased recovery of shoreline protection from wave action and erosion. Therefore, the combined benefits are multiple and, with proper planning, design, funding, governance, local support, and implementation, this can have long-lasting impacts in restoring coastal social-ecological resilience, and overall ecosystem services and productivity.

### 4.8. The challenge of engaging the youth: lessons learned from marginalized small island communities

Coral farming and reef rehabilitation in Culebra Island have also contributed to educate local children and modify local resident's behavior favoring coral reef conservation. Local NGO Coralations has developed for nearly two decades a highly successful educational engaging program called "*Exploradores Marinos*" or *Marine Explorers*. This has allowed approaching local kids with an understanding of their community relationship with the coastal resources (e.g., recreation and sustenance), and introduce planned, inquiry-based discoveries that sprout from that identity origin, as opposed to introducing a totally different perspective (e.g., "welcome to your ocean laboratory"). Second, it is important to understand that planning is compromised for families living on financial brink and that time must be budgeted to compensate for disorganization, lack of preparation, competing programs, transport, last-minute emergencies, health, and poor-diet related illnesses. Such conditions become critically magnified due to the small size of Culebra Island (<70 $km^2$), its location 27 km off northeastern Puerto Rico, and its small population size (<2000 residents). Also, programs need to be no cost for economically compromised participants, however, engagement must require compensation for programs to be valued. Required community service is one option, but always rewarded and never treated as punishment.

All developing humans seek attention. They quickly learn that attention is rewarded for both positive and negative behaviors. Many at-risk youth are conditioned to negative behavioral awards from a very young age but ocean therapy allows them to be removed from their familiar territory for rapid and constructive positive reward programming. However, the positive reward scenarios need to be well thought out, safe and many times staged in advance (e.g., collaborative removal of derelict fishing gear from the reef, recovering of lose coral fragments at risk to support coral farmers, etc.). Medical disclosures from juvenile community volunteers are sometimes dishonest because parents are concerned their child would be stigmatized or prevented to participate in the project. This is dangerous for seizure-related illnesses and inquiries have to be conducted discretely with parents in a climate of trust. This shows that parents consider coral farming and reef conservation-oriented education as unique, novel, enriching experiences for their kids, that they would do anything to ensure their participation in the project. But such risks need to be addressed in a case by case scenario to prevent kids with potentially threatening conditions to engage into risky in-water activities.

An important lesson of working with kids has been to focus activities on accomplishing missions, and refocus anxious students on a defined mission. It is also important to keep groups small and develop excursions that force interdependent collaborations. This increases cost of outreach and educational programs but reaps the rewards 10-fold in many benefits, including greater probability of interesting animal encounters and less opportunity for accidents. This can be done by matching the student to skill level contribution in team activity, and while the skills of some exceed that of others, emphasis must be kept on the importance of all individual contributions to the success of the overall defined mission. Young adult behaviors are conditioned by peer to peer interactions. Everyone is not equal, but it is important to try and find where the kid excels and expose that to other kids.

When dealing with outreach and educational activities for kids, if it is not fun, there will be no long-term engagement. Even a specifically defined work mission has to be fun in order to maintain youngsters engaged. The most be beneficial asset to engaging younger students to the program is mixing with fully engaged slightly older students. Lessons introduced cannot feel like lessons and one of the best methods has been found to be ensuring information is redundant interrogative approach. One of the most successful approaches was when a science teacher at school was offering almost identical information onto what the kids were seeing, feeling, and experience in water during their out-of-school participation in coral reef conservation educational activities.

But a roadblock to success is the rapidly increasing use of electronic devices by young students. Heads must be out of their apps. Electronics have to be confiscated with the understanding that kids, like many adults, are addicted to these devices, or there is competing attention. Also, kids behavior and attention during educational activities are affected by diet. Sometimes kids can exhibit uncontrolled or even violent reactions if allowed to eat food items with excessive content of sugar, high fructose corn syrup, and artificial colorants which they are often conditioned to eat. Nevertheless, hands-on in-water educational experiences are always behavior-transforming experiences that have shown to have multiple positive benefits for local kids. The most important elements have been getting to know their backyard marine resources, improving their respect for adults, their behavior with other kids, and their appreciation for their own resources and the benefits they derive from them.

In the long term, building up a local meaningful voice—ownership—pride of their resources, their natural reserve, and their island has always been a key mission focus of the community service projects in the hope it may help prevent the slippery slope tragedy of the commons rationalizations which could lead to continuing resource overexploitation. These approaches can probably be the only hope for a natural reserve with well-documented enforcement problems associated to poor governance, patrolling and compliance, and lack of public education and outreach. Also, in the long term, participation in local snorkeling activities moved to Friday mornings in Culebra Island has shown that participant kids perform better in school throughout the rest of the day. Therefore, such behavior-modifying activities can contribute to improve performance in schools and overall attitudes. This is an aspect that deserves to be studied, as youth represent the future of base-community participation in the management of social-ecological systems.

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The "*Educadores Marinos*" program has produced a few successful stories with kids pursuing careers in Environmental Sciences and other professional disciplines in academic institutions. For many others, the end point for *explorers* is intervention/interpretation jobs and the collaboration/participation in pilot research projects being conducted in Culebra. However, expectations are something that need to be addressed. When working with at-risk youth hope that at the end of the years, one will at least have forged a relationship/dialog with the soon-to-be young adult. Respect has to be earned with their kids and their parents to ensure engagement and support.

## 5. Conclusions and recommendations

Low-tech coral farming and reef rehabilitation have become important tools to foster community-based participation in the management of coastal social-ecological systems. But, there are still important gaps that need to be addressed in order to integrate the technical and scientific components of coral farming and reef rehabilitation with the sociological components. Preliminary evidence of Acroporid corals demographic dynamics has already shown important lessons learned. First, conservation and restoration activities should be designed at the species-specific level whenever possible, with separate specific goals and objectives for individual species. Each coral species, and even different genetic clones within any given species, can respond differently to environmental variation. Also, species-specific variability in acclimation responses to changes in environmental conditions suggests that there can be different vulnerabilities and, as such, restoration projects should always consider such variation among species. This could trigger multiple nonlinear responses to environmental and climate variation. Therefore, coral reef rehabilitation efforts must be adaptive and focused on maximizing resilience as a long-term goal. It should also look forward to develop strategies and techniques to propagate multiple coral species with different life traits to buffer against future nonlinear impacts. The resilience approach emphasizes on managing nonlinear dynamics, thresholds, environmental and climate uncertainty, and ecological surprises [51]. It also pays attention to how periods of slowly evolving, gradual change interplay with periods of rapid, stochastic change, and how such dynamics interact across different temporal and spatial scales. In this context, demographic modeling becomes fundamental to address such concerns.

Second, spatiotemporal differences in demographic transitions displayed by corals such as *Acropora cervicornis* suggest that restoration efforts should be partitioned among several locations rather than allocating all the resources into one site. Further, it also suggests that a combination of *in situ* (e.g., underwater) and *ex situ* (e.g., land-based coral aquaculture farms) strategies should be implemented to cope with potential impacts of extreme weather events and ecological surprises. These actions will enhance the persistence of the species if localized extirpation occurs due to any significant disturbance (e.g., recurrent runoff events, hurricanes). It should also foster the propagation of multiple coral species in support to coral biodiversity restoration and seascape enhancement efforts. Another fundamental lesson learned is that addressing differences in population dynamics among coral colony size categories is important for parameterizing demographic models. This may allow addressing contrasting species-specific, size-specific, genetic clone-specific, or condition-specific population trajectories. Such contrasting population trajectories may be the result of different life traits and different susceptibilities to low and moderate environmental changes. Identifying spatiotemporal variation patterns in such elements may imply that continuity in low-tech coral farming and out-planting efforts is fundamental to sustain restored populations in the wild. In addition, transplanting large colonies will result in higher population survival and growth rates than transplanting small colonies, as many standard coral farming operations do, at least across the Caribbean. Also, transplanting large colonies can achieve faster ecological benefits (e.g., thicket formation, enhanced-essential fish habitat role). However, transplanting large colonies pose some challenges; specifically, regarding the time necessary for a nursery-reared coral fragment to reach the effective transplantation size. This means that efforts need to be taken to improve coral farming techniques to accelerate coral growth, ensure high survival rates, and use methods that trigger faster colony growth rates.

It is also central to establish auto-sustainable funding mechanisms to support coral farming and reef rehabilitation projects. Demographic evidence has already proved that only through sustained input of harvested corals restored populations can remain viable and grow under present and projected environmental and climate conditions. Therefore, supporting the continuous operation of such projects becomes increasingly important, but at the same time increasingly challenging, in particular for developing countries, economically and politically constrained colonies, and small island nations. Depending only on funding through government agencies has shown to be a poor mechanism for support. Government support could be even nonexistent in many countries. Government institutions have often highly changing agenda, which typically respond to highly fluctuating political steering and philosophies in regards to natural resource conservation and climate change. Therefore, funding programs can frequently change goals and objectives, which could risk local support of projects, regardless of their historical trajectory and success. Coral farming and reef rehabilitation need to be incorporated into natural resource conservation and restoration public policies, and also into climate change and SLR adaptation strategies and policies. A potential sustainable strategy for economic support could be implementing a green tax at local or national levels (e.g., tourism activities, cruise-ship visits, airplane landings, hotel room rental, vehicle sales, property construction tax, and industrial revenues). This may include measures such as those implemented in the state of Hawai'i, USA, where coastal development projects are required to economically support State-led coral farming and reef restoration operations as part of mandatory environmental mitigation regulatory requirements.

On the other hand, increasing the spatial scale of reef rehabilitation is essential for reef rehabilitation to become an important strategy to restore coastal social-ecological systems resilience. Population demographic dynamics in *Acropora palmata* and *A. cervicornis* vary considerably in time and space. Increasing the spatial scale of population rehabilitation will increase the probability of species persistence, and will enhance its ecosystem functions (e.g., fish nursery ground, buffering wave action). Coral out-plant spatial array is also critical for the formation of thickets. In this sense, coupling demographic modeling with oceanographic numerical models is a highly promising tool to support planning, designing, and implementing future coral reef rehabilitation efforts.

But, the sociological and economic components of coral reef rehabilitation have still remained out of the formula. Understanding sociological dynamics should become an absolute priority to improve the success of future coral farming and reef rehabilitation efforts. Projects developed in Culebra Island, Puerto Rico, since year 2003 have contributed to educate local children and modify local residents' behavior favoring coral reef conservation. Particularly, addressing behavior-modifying activities and learning how to overcome roadblocks to success are fundamental to develop sustainable strategies to educate, train, and empower local residents to participate in social-ecological systems management. It is critical to foster the creation of strong, functional, cross-sectorial partnerships, which respect the integration of base communities and small non-governmental organizations (NGOs) in the planning and implementation of projects. The stronger the environmental governance collaboration, the improved the success in addressing problems in social-ecological systems [52].

But also, understanding of social processes like social learning and social memory, mental models, and knowledge–system integration are a critical trans-disciplinary integration to improve projects success and social-ecological systems resilience [51]. Further, integrating visioning and scenario building, leadership building, multi-sectorial agents and actor groups, and strengthening cross-sectorial social networking are necessary adaptive approaches to cope with future environmental and climate changes. Another particular challenge of social-ecological systems is how to deal with institutional and organizational inertia and change, with adaptive capacity, transformability, and systems of adaptive governance that allow for management of essential system services [51]. Further, strengthening adaptive governance capabilities is essential to overcome stochastic events and crisis (e.g., natural disasters; ecological surprises). Strong governance connects individuals, organizations, agencies, and institutions at multiple organizational levels [53]. Further, building vision, leadership, and trust are also important features of resilient social-ecological systems [54]. Strengthening the organization of base communities can empower key persons to provide leadership, trust, vision, meaning, and they help transform management organizations toward a learning environment, and can foster the participation of at-risk youth, and the integration of adaptive, participatory co-management efforts. A resilient social-ecological system may make use of crisis as an opportunity to transform into a more desired state.

In addition, the following 10 components have been shown to be fundamental to address sustainable and resilient social-ecological systems [55]: (1) *Size of resource systems*—in our case, the spatial scale of reef rehabilitation becomes a major element of concern to achieve sustainability and meaningful impacts on resilience; (2) *Productivity of system*—increasing the spatial scale of reef rehabilitation also fosters an increase in ecological and social benefits; (3) *Predictability of system dynamics*—the incorporation of restored coral demographic models, coupled with oceanographic numerical models, should be the next step to improve our ability to predict system dynamics; (4) *Resource unit mobility*—corals are not mobile entities, but reef-associated biota can be, therefore, improving governance regarding management of mobile links such as reef fisheries is important to improve management success; (5) *Collective choice rules*—fostering increased local participation in planning and decision-making processes will increase local stewardship, support, and compliance with management, and may reduce cost and difficulties of enforcement; (6) *Number of users*—the impact of group size and determining limits of acceptable change (from the perspective of recreational and tourism uses) must be incorporated into management; (7) *Leadership/entrepreneurship*—developing leadership and entrepreneurship skills in members of local base communities is paramount to improve stewardship, support and trust, and would likely result in the protection of local livelihoods and business opportunities; (8) *Norms/social capital*—need to build up shared moral and ethical standards, and common trust in resource users to facilitate decision-making and monitoring processes; (9) *Knowledge of social-ecological systems/mental models*—knowledge of social-ecological systems is central to share common knowledge among different user sectors, to understand carrying capacity and limits of acceptable change of the resource, its attributes of resilience, and to prevent failure to organize and destroy the system; and (10) *Importance of resource*—understanding the value of the resource to local environmental, ecological, and socio-economic sustainability, to the support of sustainable livelihoods, and for sustaining food security and sovereignty. The take-home message is that reef managers and reef rehabilitation practitioners need to engage social scientists to support their efforts as a strategy to foster improved local support, stewardship, compliance, and success.

Coral reef rehabilitation in Culebra Island, Puerto Rico, has resulted in a rapid increase in benefits for local communities. Increasing tourism and business opportunities have resulted in a significant boom in gross revenues for private businesses, and in improved, and diversified livelihoods. This has resulted in increasing alternative job opportunities. But, leakage of revenues needs to be reverted to enhance sustainability, local benefits, stewardship, and support. Coral reef rehabilitation has also resulted in increasing fish densities on rehabilitated reefs, therefore attracting further nature-based tourism, and in contributing to enhance fishing on adjacent areas, through fish spillover effects. In addition, it has resulted in increased recovery of shoreline protection from wave action and erosion. Therefore, the combined benefits to social-ecological systems are multiple, and with proper planning, design, funding, local support, and implementation this can have long-lasting impacts in restoring resilience and overall services and productivity of coastal social-ecological systems.

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