BULLETIN OF MARINE SCIENCE. 88(4):1075–1098. 2012 CORAL REEF PAPER
http://dx.doi.org/10.5343/bms.2011.1143

A REVIEW OF REEF RESTORATION AND CORAL PROPAGATION USING THE THREATENED GENUS *ACROPORA* IN THE CARIBBEAN AND WESTERN ATLANTIC

CN Young, SA Schopmeyer, and D Lirman

ABSTRACT

Coral reef restoration has gained recent popularity in response to the steady decline of corals and the recognition that coral reefs may not be able to recover naturally without human intervention. To synthesize collective knowledge about reef restoration focused particularly on the threatened genus *Acropora* in the Caribbean and western Atlantic, we conducted a literature review combined with personal communications with restoration practitioners and an online questionnaire to identify the most effective reef restoration methods and the major obstacles hindering restoration success. Most participants (90%) strongly believe that *Acropora* populations are severely degraded, continue to decline, and may not recover without human intervention. Low-cost methods such as coral gardening and fragment stabilization were ranked as the most effective restoration activities for this genus. High financial costs, the small footprint of restoration activities, and the potential damage to wild populations were identified as major concerns, while increased public awareness and education were ranked as the highest benefits of coral reef restoration. This study highlights the advantages and outlines the concerns associated with coral reef restoration and creates a unique synthesis of coral restoration activities as a complementary management tool to help guide "best-practices" for future restoration efforts throughout the region.

Worldwide coral reef degradation has reached a point where local conservation strategies and natural recovery processes alone may be ineffective in preserving and restoring the biodiversity and long-term integrity of coral reefs (Goreau and Hilbertz 2005). Faced with the prospect of limited natural recovery due to low rates of sexual recruitment, low recruit survivorship, and highly variable reproductive and settlement events (Kojis and Quinn 2001, Bruckner 2002, *Acropora* Biological Review Team 2005, Quinn and Kojis 2005), researchers and managers are turning to active reef restoration as a potential mechanism to both mitigate declining patterns and enhance potential recovery of damaged or depleted coral populations (Guzman 1991, Rinkevich 2005, Precht 2006, Edwards and Gomez 2007). While active restoration is a widely accepted practice for wetlands (Zedler 2000), saltmarshes (Laegdsgaard 2006), oyster reefs (Coen 2000, Coen et al. 2007), mangroves (Field 1999, Lewis 2005), and seagrasses (Thorhaug 1986), the field of coral reef restoration is relatively new, highlighting the pressing need to formulate, evaluate, and disseminate effective and cost-efficient methodologies and management strategies to interested stakeholders.

During its infancy, reef restoration focused mostly on structural or engineering solutions to repair natural breakwaters that protect valuable coastlines from erosion or restoring structural integrity and topographical complexity to reefs damaged by ship groundings and blast fishing (Precht 2006). Artificial structures, such as Reef Balls (www.reefball.org), have been designed to provide shoreline protection and prevent beach erosion while also creating substrate for natural recruitment and attachment of benthic organisms such as corals and sponges. However, in the 1970s–1980s, restoration efforts began to focus on restoring the biological and ecological function of coral reefs by transplanting coral fragments or colonies (Maragos 1974, Bouchon et al. 1981, Abelson 1982, Harriott and Fisk 1988). Large-scale ecological coral restoration projects were first conducted in the Indo-Pacific and the Red Sea in the 1990s (Rinkevich 1995, Oren and Benayahu 1997, Treeck and Schuhmacher 1997).

At present, one of the most commonly used coral propagation and restoration methods is "coral gardening" (Rinkevich 1995, Bowden-Kerby 2001, Epstein et al. 2003, Shafir et al. 2006, Shafir and Rinkevich 2008, Shaish et al. 2008). This method, adapted from terrestrial silviculture, consists of removing a limited amount of tissue and skeleton (from a few polyps to small branches) from healthy wild coral populations and propagating an initial stock within in situ or ex situ coral nurseries. Nursery-grown colonies produce a sustainable stock of corals which can then be transplanted to degraded reefs (Rinkevich 1995, 2005, Epstein et al. 2001, 2003, Soong and Chen 2003). Developed initially in the Indo-Pacific and Red Sea regions, coral gardening methods have been increasingly implemented in the Caribbean (see Table 1), where efforts have targeted almost exclusively the branching corals *Acropora cervicornis* (Lamarck, 1816) and *Acropora palmata* (Lamarck, 1816), which were once the dominant reef-building taxa in the region. Due to the combination of biological and anthropogenic stressors, *Acropora* has suffered significant degradation with estimated population declines of up to 95% in some areas (Porter and Meier 1992, Bruckner 2002), leading to their listing as threatened in the US under the Endangered Species Act in 2006 (Hogarth 2006) and as critically endangered in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species in 2008 (Aronson et al. 2008, Carpenter et al. 2008).

Acroporid corals are critically important for reef growth, island formation, fisheries habitats, and coastal buffering. Both acroporid species exhibit particularly high growth rates relative to other corals (Goreau and Goreau 1959, Shinn 1966, Glynn 1973, Gladfelter et al. 1978), enabling sustained reef growth during previous sea level changes. Additionally, both species exhibit unique branching morphologies, providing essential habitat for other reef organisms. Thus, it is unlikely that any other Caribbean reef-building species is capable of fulfilling these specific ecosystem functions. Therefore, it is probable that the continued decline of *Acropora* will cause considerable losses in reef function and structure (*Acropora* Biological Review Team 2005).

To combat the decline of Caribbean acroporid corals and assist in their recovery, an increasing number of practitioners are conducting restoration and propagation activities with this genus (Bruckner and Bruckner 2001, Quinn et al. 2005, Quinn and Kojis 2006, Herlan and Lirman 2008) and extensive, albeit largely unpublished or undocumented, collective knowledge exists on the effectiveness of such activities. *Acropora* species are considered good candidates for use in restoration or population enhancement projects due to their high growth rates, natural use of fragmentation for asexual reproduction, ability to heal rapidly from wounds, and high survivorship of fragments as compared to other coral species (Gladfelter et al. 1978, Tunnicliffe 1981, Bak and Criens 1982, Highsmith 1982, Lirman et al. 2010). In the present study, we use a combination of literature and case-study reviews, personal communications with restoration practitioners, and an online questionnaire to formally compile the collective knowledge of the coral restoration community on the status of reef restoration activities in the Caribbean region. We concentrate on *Acropora* restoration and propagation projects to provide a review of methods used, as well as lessons learned from these activities.

While reviews and manuals based on reef restoration projects in the Pacific have been already published (Jaap 2000, Omori et al. 2004, Rinkevich 2005, Edwards and Gomez 2007, Edwards 2010), only one restoration manual exists for the Caribbean (Johnson et al. 2011). Our study complements this manual by providing a full review and analysis of reef restoration projects in the Caribbean, and more specifically, projects related to the threatened Caribbean *Acropora* species. Due to the unfortunate paucity of published literature and data regarding reef restoration in the Caribbean, this study fills important knowledge gaps by collecting information from any and all available sources (published and gray literatures). By synthesizing this collective information, we determined the restoration methods that have proven the most cost-effective and efficient, as well as which factors are having the highest impact on reef restoration success rates.

Methods

The present study included two main activities: (1) a literature review of propagation and restoration projects with an emphasis on those focused on the threatened genus *Acropora* in the Caribbean, and (2) an online questionnaire developed to compile up-to-date collective knowledge and opinions of reef restoration researchers and practitioners.

The literature review was conducted to identify different types of coral reef restoration projects implemented in the Caribbean. Information was gathered using database mining of the web, review of published materials and gray literature, postings in email groups, and personal communications. Practitioners received identical emails requesting project summary information (i.e., site location, species used, methods, highlights, recommendations, concerns, and disturbance factors) and lessons learned (what worked and what did not work). Basic summary statistics were compiled to identify patterns and trends in topics such as propagation and restoration methodologies, coral reef restoration concerns, and recommendations. Personal contacts (conducted in the native language of the respondent) were made only in cases where basic project information (i.e., location, dates, species used, methods, survivorship and growth, disturbance factors) were missing or not available from the sources reviewed, and only missing data were requested during these communications.

Finally, an online questionnaire was drafted to elicit expert opinions among Caribbean coral reef restoration researchers, scientists, managers, and gain perspective from other restoration participants such as students, volunteers, and industry professionals (Online Appendix 1). The instrument was posted on email list-servers, including the Caribbean Conservation group, *Acropora* group, and the National Oceanic and Atmospheric Administration (NOAA) Coral List. In addition, this instrument was introduced at the *Acropora* Conservation and Restoration Workshop in Washington, DC (November 12–13, 2009), to encourage practitioners to participate. The questionnaire requested information such as personal background and education level, coral reef restoration experience, familiarity with propagation and restoration methodologies, restoration concerns, and recommendations. The questionnaire was designed to identify emergent issues and concerns and provide recommendations from restoration practitioners that may affect the outcomes of coral restoration projects.

Every effort was made to distribute the questionnaire to a wide audience, and not only target practitioners that were actively working in this field, but also those who were critical of restoration efforts. The questionnaire was posted twice during a period of 3 mo after which all responses were analyzed. Responses were statistically analyzed (one-way ANOVA on ranks) to determine if answers were potentially influenced by respondent affiliation [i.e., academic, government, non-government organization (NGO), etc.] or level of experience based on number of years involved in reef restoration. If no statistical differences were detected among groups, data were pooled for further analyses.

It is important to highlight some caveats of this questionnaire and its interpretation. While every effort was made for the questionnaire to reach a wide audience, no information is available on the actual size of the population of restoration practitioners and, thus, it is impossible to know the proportion of the total population that the 79 respondents represent. Therefore, it is unclear how representative of the whole population this sample is. Also, common survey design errors such as sampling, non-response, and non-coverage errors could not be quantified, precluding the implementation of correction factors and weighing techniques applied in more formal surveys (Dillman 1991, 2007). While these issues limit the extrapolation of general conclusions about the value and benefits of reef restoration beyond the group sampled, we believe that the review of methodologies is robust and represents the best-available compilation of collective knowledge on the topic of reef and *Acropora* restoration in the Caribbean region. By asking practitioners to limit their rankings of methodologies to those that each respondent had actually tested, we are able to provide a synthesis of expert knowledge on these issues.

Results

Caribbean *Acropora* Restoration Projects.—Over 60 *Acropora* restoration projects were identified from 14 Caribbean countries and island nations as part of this review (Fig. 1, Table 1). Of these projects, 48% used *A. cervicornis*, 12% used *A. palmata*, and 40% used both *Acropora* species. The coral gardening methodology was the pre-eminent method used in 63% of projects for the propagation of this genus. Within coral nurseries, *Acropora* fragments have been grown on frames, ropes, cinderblock platforms, Reef Balls, floating structures, and through electrolysis processes known as the BioRock method (Table 2, Figs. 2A, 3). The use of metal frames in propagation projects was the most common methodology since stainless steel mesh is readily available, relatively inexpensive, experiences reduced corrosion, and is resistant to storm damage. The propagation of *Acropora* on metal frames has been shown to be successful with most projects documenting 63%–95% survival. Additionally, increased survival (86%–97.5%), coral growth (up to 21.0 cm^{-1}), and reduced predation have been documented when propagating fragments on suspended mid-water line nurseries, which were used in 42% of projects (Bowden-Kerby et al. 2005, Quinn and Kojis 2006, Johnson et al. 2011, Nedimyer et al. 2011; Fig. 3B). Practitioners often recommended that prevention of predation and regular maintenance are vital to coral survival within coral nurseries.

While some projects (12.5%) focused on simple fragment stabilization or transplantation of corals onto natural reefs after physical disturbances such as ship groundings or storms (Garrison and Ward 2008, Bruckner et al. 2009), almost 60% of projects outplanted nursery-grown corals onto degraded reefs or artificial structures as a final restoration step (Hernández-Delgado et al. 2001, Johnson et al. 2011). A variety of attachment platforms were used for outplanting corals, including Reef Balls, cement pucks, and concrete rosettes (Table 1, Fig. 3). In addition, coral fragments or colonies were transplanted directly onto the reef substrate using cement, underwater epoxy, plastic cable ties, metal wire, nails, bolts, or direct wedging into crevices (Fig. 2B). Many studies found the use of small plastic cable ties to be a cheap, quick, and effective method for attaching corals to artificial or reef substrate (Bruckner et al.

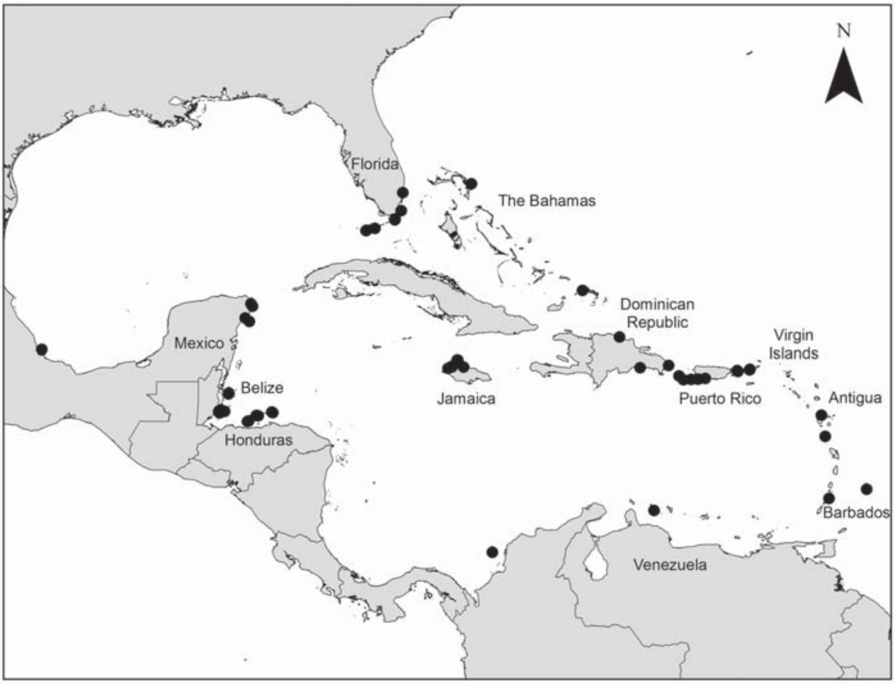

Figure 1. Map of the Caribbean, western Atlantic, and Gulf of Mexico with the location of *Acropora* restoration and propagation sites identified in this review.

2009, Forrester et al. 2010, Williams and Miller 2010, Johnson et al. 2011, Garrison and Ward 2012). In the Caribbean, Reef Balls have been used specifically for transplanting *Acropora* in 22% of projects. Larval seeding (5% of projects) has only been used in a limited number of studies to restore depleted reefs, but is often expensive, time consuming, and with limited success (Sammarco et al. 1999, Precht 2006). Many projects in the Caribbean have used more than one propagation method to culture coral fragments and multiple attachment methods to ensure restoration success based on specific local environmental conditions (Bowden-Kerby et al. 2005, Quinn et al. 2005, Williams and Miller 2010, Johnson et al. 2011).

Due to the paucity of published literature documenting the status of *Acropora* nursery programs in the Caribbean, most available information was mined from project pages provided by nursery and restoration practitioners (see Table 1). Overall, nursery programs throughout the Caribbean have been highly successful in increasing the biomass of *Acropora* after limited tissue collections from wild "donor" populations. High survivorship (>70%) of coral fragments has been found within coral nurseries during the first year of propagation. Coral mortality was often due to storm damage or other disturbances such as temperature anomalies (Hernández-Delgado et al. 2001, Quinn and Kojis 2006, Schopmeyer et al. 2011), although predation and poor water quality have also been identified as factors leading to mortality of nursery corals indicating that success rates of nurseries are highly site-specific. For example, in Puerto Rico and the Dominican Republic, cumulative survival of *A. cervicornis* propagated on metal A-frames was 65%–95% during the first year, whereas a coral nursery established using the same methods in Guanaja, Honduras, suffered

Table 1. *Acropora* propagation and restoration activities throughout the Caribbean and western Atlantic. Reef Balls are used extensively as artificial reef substrate for coral propagation but are not listed individually in this Table (see www.reefball.org). Methods key: B = Bolts/Nails, BR = BioRock, CB = Concrete blocks, CBL = Cable ties, EC = Epoxy or cement, F = Frame nursery (Wire mesh or PVC), FR = Floating rack, FS = Fragment stabilization, L = Line nursery, O = Outplant, S= Attached to skeleton, SR = Sexual recruit, T = Transplants, TR = Tree nursery, W = Wire, WD = Wedging. AC = *Acropora cervicornis*, AP = *Acropora palmata,* APR = *Acropora prolifera*.

Country	Location	Species	Methods	Highlights	Contact (reference/link)
Belize	Multiple locations	AC, AP	CB, F, L	Used three different propagation methods; main concerns were bleaching, predation, and storms.	L Carne/A Bowden-Kerby (www.coralsforrestoration.com)
British Virgin Islands	Guana Island	AP	EC, CBL, S, T	Securing fragments to the substrate increases growth and survivorship regardless of attachment method. Clearing macroalgae promotes long-term growth. Transplant shock caused by white syndrome and damselfish observed. No long-term effect after 3 months.	G Forrester (Forrester et al. 2011, 2012)
Colombia	Bird Island	AC, AP	L	Surveys indicate *Acropora palmata* populations in the Rosary Islands have experienced 99% mortality, nurseries contain 15 distinct genotypes of AC and AP; main concern is muddy freshwater discharge from Canal del Dique during rainy season.	M Herrera (www.savefvc.com)
Curaçao	Sea Aquarium	AC, AP	SR	Collected spawn during mass spawning events and cultured larvae, outplanted freshly settled recruits and cultured sexual recruits in nursery, established ex situ population in public aquaria around the world, established a cryobank for frozen coral material.	D Petersen (www.SECORE.org)
Dominican Republic	Boca Chica	AP	CBL, CP, T, W	200 elkhorn colonies stabilized on reef after hurricane, 95% survival over first year, 50% of colonies sheathing over the substrate, spawning observed 3 yrs after transplantation; main concerns included hurricanes and predation by snails and worms.	B Bezy (University of Costa Rica, pers comm)
Dominican Republic	Punta Cana	AC	F, L, O	Biomass increase 8–10× yr^{-1}, 300 fragments outplanted, mortality on frames and ropes low (<5%), main concerns were predators, cyanobacteria, wave action/breakage, and bleaching.	A Bowden-Kerby (http://www.counterpart.org/our-work/projects/coral-gardens-in-dr)
Dominican Republic	Sosua	AC	F, L	High initial survivorship (90%), rapid branch growth, high mortality (75%) due to frame collapse; main concerns were predators, poor water quality, and algae.	A Bowden-Kerby (http://www.counterpart.org/our-work/projects/coral-gardens-in-dr)
Guadalupe	Grand Cul-de-Sac Marin	AC, AP	L	100% survivorship for elkhorn and 95% survivorship for staghorn after 102 d, mean weight increase of 219% for staghorn and 65% for elkhorn, staghorn had better growth when suspended in open water while elkhorn had better growth when attached to the bottom.	C Bouchon (http://www.nova.edu/ncri/11icrs/abstract_files/icrs2008-001662.pdf)
Honduras	Roatan—multiple sites	AC	F, L	9% survival on trays, 32% survival on frames, 41% survival on ropes after 11 mo; main concerns were predation from four-eye butterfly fish, disease, and algal overgrowth.	A Bowden-Kerby (www.counterpart.org/our-work/projects/coral-gardens-in-honduras)
Honduras	Guanaja—multiple sites	AC	F, L	Rapid growth and low mortality after 1 yr, platform failure resulted in high mortality; main concerns were hurricanes, poor water quality, low circulation, predation (fireworms especially problematic) and algae.	A Bowden-Kerby (www.counterpart.org/our-work/projects/coral-gardens-in-honduras)

Table 1. Continued.

Country	Location	Species	Methods	Highlights	Contact (reference/link)
Honduras	Utila—multiple sites	AC	F, L, O, WD	70% survival on trays and 72% survival on frames after 11 mo, 217 fragments were plugged into reef rock with 53% survival/attachment and doubling in size within 1 year, diseases increases as corals grew bigger (frequent trimming recommended to avoid over-maturation); main concerns were predation, wave action/breakage and algae, vandalism and loss of materials resulted in coral losses.	A Bowden-Kerby (www.counterpart.org/our-work/projects/coral-gardens-in-honduras)
Jamaica	Discovery Bay—multiple sites	AC	F, L	82% survival after 39 wks and 68% survival after 62 wks; 159% increase in biomass, higher survival on ropes than on frames; main concerns were hurricanes, predation, damselfish, and algae.	A Bowden-Kerby (http://www.artificialreefs.org/ScientificReports/A.cervicornisrestorationPresentedat-CoastalZone2005.pdf)
Jamaica	Discovery Bay	AC	BR	High growth rates and dense branching, corals readily attached to substrate, juvenile coral recruitment found on 3-yr-old structures, reduced algal growth on structures compared to nearby natural reefs; concerns include storm and boat damage, predation.	T Goreau (http://globalcoral.org/reef_restoration_using_seawater.htm)
Jamaica	Montego Bay	AC	F	Nurseries established using A frames, growth and survivorship higher on frames placed on sand patches due to protection from predators, higher algal overgrowth on small-mesh frames, securing frames with cinderblocks created damselfish habitat.	A Bowden-Kerby (http://www.artificialreefs.org/ScientificReports/A.cervicornisrestorationPresentedat-CoastalZone2005.pdf)
Jamaica	Montego Bay	AC	L	97.5% survivorship and 10× fragment growth over 10 mo, slower growth and less branching at deeper site, ropes limited fouling and damselfish colonization, hydroid damage and damage to lines by fish traps were observed.	A Ross (http://www.nova.edu/ncri/11icrs/abstract_files/icrs2008-000990.pdf)
Jamaica	Oracabessa Bay	AC, AP	L, O, W	1000 corals on ropes, ropes can be moved before storms; main concern is algal overgrowth, 200 corals outplanted.	A Ross (Johnson et al. 2011)
Mexico	Veracruz	AP	EC, F, O	Corals kept on PVC racks attached to reef, 90% survivorship after 2 mo and 80% after 8 mo, growth of up to 6 m in 8 mo, initial cement mix and applicator not successful, 3600 fragments outplanted; main concern was spacing, fragments placed too close together experienced high predation.	G Nava (Johnson et al. 2011)
Mexico	Cancún—Isla Mujeres	AC, AP	CB	>900 fragments in in situ and ex situ nurseries, tested whether feeding (*Artemia*) accelerates growth, >30% mortality at reef crest due to poor water quality; algal overgrowth was main concern.	JG Cano, JC Huitrón Baca (Johnson et al. 2011)
Puerto Rico	Culebra—Bahia Tarja	AC	CB, EC	>90% survivorship of fragments cemented to reef after 9 mo, growth of 60% for staghorn and 66% for elkhorn after 10 mo; mortality due to predation by damselfish was main concern.	E Hernández-Delgado (Hernandez-Delgado et al. 2001)
Puerto Rico	Culebra—Tamarindo	AC	B, F, O	83%–93% survivorship, up to 17% mortality of during first month due to sediments and water quality.	E Hernández-Delgado (Hernandez-Delgado 2004)

Table 1. Continued.

Country	Location	Species	Methods	Highlights	Contact (reference/link)
Puerto Rico	Culebra—Punta Soldado	*AC*	B, F, O	99% survivorship at nursery after 4 mo, 98% survivorship of outplanted corals after 8 mo.	E Hernández-Delgado (Hernández-Delgado 2004)
Puerto Rico	La Parguera—Multiple Sites	AC, AP	CB, F, L	30%–74% survival of 3–5 cm fragments, 74%–87% survival of 8–12 cm fragments, and 70%–97% survival of 15–22 cm fragments placed on rubble after 6–7 mo, 100% mortality of fragments placed on sand; one site completely buried by Hurricane Hortense; main concern was storms.	A Bowden-Kerby (Bowden-Kerby 2001)
Puerto Rico	Rincón	AP	SR	Established ex situ population in public aquaria around the world, established a cryobank for frozen coral material, viable gametes distributed in three genome repositories, outplanted freshly settled recruits; main concerns were sedimentation, storms, waves, and intervention/removal by tourists.	I Baums (Baums et al. 2005, www.SECORE.org)
Puerto Rico	Mona Island—Fortuna Reefer Grounding	AP	B, CBL, FS, W	1857 coral fragments stabilized on reef damaged by Fortuna Reefer, 57% mortality during first 2 yr and 80% after 6 yr, <10% fragments alive after 10 yr; main concerns were wave surge, wire abrasion, fragment removal, overgrowth by clionid sponges, disease, and predation by corallivorous snails.	A Bruckner (http://www.nova.edu/ncri/11icrs/abstract_files/icrs2008-000750.pdf)
Puerto Rico	Bahía de Tallaboa—Margara Grounding	AC	EC, CBL, FR, O	Floating Underwater Coral Apparatus (FUCA) frames used for propagation at site, >1500 coral at nursery, >900 fragments reattached at grounding site, vigorous fragment growth and branching, 10% survivorship of outplanted corals, good circulation and fish for cleaning ropes are desirable.	S Griffin, T Moore (Johnson et al. 2011)
Turks and Caicos	Grand Turk—multiple sites	AC, AP	BR	Increased growth over attachment wires, 30%–40% coral mortality due to hurricane, limited hurricane damage to structures due to low drag of open structures.	L Wells (Wells et al. 2010)
USVI	St. John—Whistling Cay	AP	CBL, T	55% survivorship after 1 yr, 80% mortality after 5 yr, fragment dislodgement main cause of mortality.	V Garrison (Garrison and Ward 2008)
USVI	St. John—multiple sites	AC, AP	CBL, S, T	12 yr study of transplanted storm-generated fragments to dead AP skeletons, 9% fragment survivorship, higher survival of AP than AC, 56% mortality due to dislodgement, fragment mortality rates similar to reference/wild colonies, survival dependent on fragment size.	V Garrison (Garrison and Ward 2012)
USVI	St. Thomas and St. Croix—multiple locations	AC, AP	CB, FR, TR	Trade off between water quality and growth rates, nursery site selection is key for nursery success, regular maintenance required to prevent fouling/predation and to document stress effects, storm damage and algal/hydroid overgrowth major concerns.	K Amon-Lewis (www.nature.org)
United States	Florida Keys—connected grounding	AP	EC, FS	370 fragments attached to cement reef crowns, good survivorship and growth over bases after 3 yr, mortality due to disease and corallivorous snails, main concern was breakage due to hurricanes.	J Schittone (http://sanctuaries.noaa.gov/protect/restoration/welcome.html)

Table 1. Continued.

Country	Location	Species	Methods	Highlights	Contact (reference/link)
United States	Florida Keys—Dry Tortugas	AC, APR	CB	Local knowledge of reef area and weather conditions key to nursery success, consider difficulties when working in remote locations; bad weather and remote location were concerns.	M Johnson (www.nature.org)
United States	Florida Keys Key West	AP	EC	Corals attached to cement rosettes, new growth evident after 1 mo, units became fish habitats, 80% of fragments lost due to hurricane, disease prevalent after first 2–3 mo.	C Quirolo (http://coralrestoration.org/CRF/index.php?option=com_content&view=category&layout=blog&id=62&Itemid=101)
United States	Florida Keys—Key Largo	AC	EC, O, T	12%–45% mortality over first 2 mo, mortality from disease and snail predation, mortality influenced by source population and transport distance.	M Miller (Miller et al. 2010)
United States	Florida Keys—Jacquelyne Grounding	AP	CB, EC, T	70 fragments attached to reef and rosettes using cement, good survivorship after 1 yr, restoration site destroyed by 2005 hurricanes.	J Schittone (Franklin et al. 2006)
United States	Florida—Broward County	AC	CB	22%–56% mortality after 1 mo, growth rate was 6–9 cm yr^{-1}, larger fragments (>5 cm) grew faster than smaller ones, initial mortality due to high temperature.	D Gilliam (http://www.nova.edu/ocean/ncri/research/establishment-maintenance-coral-nursery.html)
United States	Florida—Biscayne National Park	AC, AP	CB	>1000 fragments from 33 genotypes in two nurseries, fragments outplanted to 4 reef sites, genotypic differences in fragment growth, 17% mortality during first 8 wks, nurseries have become fish recruitment habitat; main concerns are temperature extremes, algae, and sedimentation.	D Lirman, S Schopmeyer (Lirman et al. 2010, Schopmeyer et al. 2011)
United States	Florida—Biscayne National Park	AP	CBL, EC, FS, T	Stabilization using cable-ties and epoxy similarly effective, marine epoxy can be safely used in contact with or adjacent to coral tissue, only 1 fragment suffered complete mortality, nine fragments lost, tissue loss underneath fragment a concern when attaching fragment to bottom.	D Williams (Williams and Miller 2010)
United States	Lower Florida Keys	AC	CB, L	13% mortality after 1 mo, 16% tissue gains during first month; main concerns were temperature extremes and storms.	E Bartels (http://isurus.mote.org/Keys/staghorn.phtml)
United States	Middle Florida Keys	AC	CB, L	Algal growth and bleaching were main concerns possibly due to influence from Florida Bay, hydroids were common on line nurseries, high mortality caused by sever cold-water event in 2010.	K Maxwell (www.myFWC.com)
United States	Upper Florida Keys	AC, AP	CB, CP, L, O, TR	>15,000 corals in nursery, multiple nursery platforms used, >1500 corals outplanted, outplanted corals spawned in 2009, regular cleaning advised, main concerns are unit/coral spacing, algae, temperature extremes.	K Nedimyer (Nedimyer et al. 2011, www.coralrestoration.org)
Multiple	Multiple locations	AC, AP	RB	Successful coral transplantation using underwater epoxy, recruitment of juvenile corals, fish and other invertebrates, high growth rates observed even in areas with poor water quality, provides shoreline protection.	T Barber (www.reefball.org)

100% mortality within the first year due to poor water quality. Biomass increases of 60%–219% have been recorded within coral nurseries and practitioners have found that utilizing larger *Acropora* fragments (>5 cm) promotes higher survivorship and productivity than with smaller fragments (Bowden-Kerby 2001, Herlan and Lirman 2008, Lirman et al. 2010). With the success of such propagation techniques, many restoration practitioners are expanding the size of coral nurseries and some currently house >10,000 corals providing a large source of corals for use in restoration activities (K Nedimyer, Coral Restoration Foundation, pers comm).

The literature review revealed high variability in the level of success of restoration activities throughout the Caribbean. In studies including coral transplantation as part of their restoration strategy, fragment survival ranged between 43% and 95% during the first year with some studies documenting an increase in biomass of up to 250% for transplanted *Acropora* (Quinn and Kojis 2006, Table 1). In other studies, >50% fragment mortality was observed within the first year typically due to fragment dislodgement or storm damage, and mortality often increased to 80%–100% after 5 yrs (Bruckner et al. 2009, Garrison and Ward 2012). However, fragment stabilization, especially with cable ties or underwater epoxy, significantly increases the survival of transplanted corals (Williams and Miller 2010) and most corals were observed to begin sheeting live tissue over attachment substrates within 3 mo of transplanting. Similar to propagating fragments within coral nurseries, transplanting larger fragments (>5 cm) resulted in higher growth rates and survivorship of outplanted acroporids. Mortality rates of transplanted corals were similar to those of reference or wild colonies showing that once transplanted, nursery-reared corals respond to environmental factors just as wild colonies (Garrison and Ward 2008, Forrester et al. 2010). Thus, many studies stressed the need to identify the underlying causes of coral mortality and reef degradation and address such issues to ensure the success of restoration activities.

The top three concerns presented by practitioners for the fragment stabilization or nursery phases of reef restoration activities were: (1) physical damage caused by waves and storms, (2) predation, and (3) competition by algae and other space competitors (i.e., sponges, bryozoans, tunicates, etc.; Fig. 2C). Increased wave action and storms can cause fragment breakage and dislodgement as well as damage to the restoration structures (Bowden-Kerby 2001, Franklin et al. 2006, Wells et al. 2010). Strategic placement of nurseries in areas with reduced wave exposure was suggested as a way to mitigate physical damage. The use of rope nurseries that can be moved to deeper water in advance of a major hurricane also provides protection to nursery stocks (Johnson et al. 2011). Predation by corallivorous snails [*Coralliophila abbreviata* (Lamarck, 1816)] and fireworms [*Hermodice carunculata* (Pallas, 1766)] and coral mortality caused by the gardening activities of territorial damselfish were highlighted as major causes of mortality to corals and most studies recommended periodic removal of predators to limit coral mortality during both nursery and outplanting phases (Hernández-Delgado et al. 2001, Miller et al. 2010). Utilizing mid-water rope nurseries that provide limited access for benthic predators was also suggested as a method to help minimize predation. Macroalgal overgrowth was highlighted as a concern in most projects and active removal of macroalgae and other fouling organisms (i.e., cyanobacteria, sponges, hydroids) was highly recommended to ensure survival of coral fragments and/or transplants (Forrester et al. 2010, Johnson et al. 2011). Other sources of concern for reef restoration ascertained from the literature

Table 2. *Acropora* propagation methods utilized throughout the Caribbean and western Atlantic.

Propagation method	Materials	Fragment attachment methods	Countries	Advantages	Disadvantages
Frames/tables	Metal grids, plastic mesh, PVC tables	Plastic cable ties, metal wire, monofilament	Belize, Honduras, Jamaica, Dominican Republic, US (Puerto Rico), Mexico	Storm resistant, placement near reef promotes grazing	Frame failure due to rust, securing frames with cinderblocks may create damselfish habitat
Ropes/lines	Polypropylene lines, monofilament	Cable ties, monofila-ment, threading	Jamaica, Belize, Dominican Republic, Honduras, US (Florida)	Positive growth rates, improved water circulation, protection from predation	Accumulation of macroalgae, susceptible to storm damage
Cinderblock platforms	Cement cinderblocks, PVC or cement pedestals, cement pucks	Underwater epoxy, cement	US (Florida, USVI)	Positive growth rate, low mortality, capable of sexual reproduction	Accumulation of sediment and macroalgae, susceptible to storm damage, epoxy failure
Reef Balls	Cement	Underwater epoxy	Antigua, The Bahamas, Barbados, Cayman Islands, Curaçao, Dominican Republic, Dominica, Mexico, Turks and Caicos	Prevents shoreline erosion, enhances fisheries, diver/snorkel/ tourist attraction, mangrove restoration, lobster/ oyster habitat, coral settlement substrate	Accumulation of macroalgae, predation, difficult to deploy or move
Floating structures	Polypropylene lines, PVC, plastic mesh	Monofilament, small plastic pedestals (golf tees), Super glue, epoxy	Jamaica, US (Florida, Puerto Rico)	Positive growth rates, protection from predation, easy outplanting	Accumulation of macroalgae, susceptible to storm damage
Larval seeding	Larvae or gametes collected in nets	Larvae settled onto coral rubble, plates or tiles	US (Florida), Curacao	Provide viable recruits for deployment on reefs, preserves genetic material	Requires ex situ culture facility, recruits may be more susceptible to outplanting than fragments or colonies

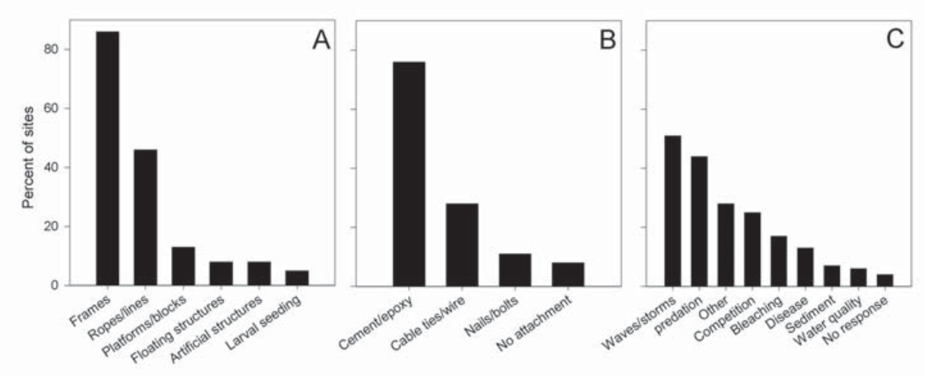

Figure 2. Percentage of Caribbean *Acropora* restoration sites (A) using various propagation methods, (B) utilizing various fragment attachment methods, and (C) experiencing common restoration concerns.

review included coral diseases and temperature anomalies, as well as increased nutrients and sedimentation. Some of these issues can be addressed by strategically placing nurseries and restoration sites away from land-based sources of pollution, within marine protected areas, and/or in deeper habitats where temperature impacts may be lessened (Johnson et al. 2011, Schopmeyer et al. 2011). Additionally, studies show that avoiding fragmentation and outplanting activities during warm summer months when water temperatures and bleaching prevalence are higher increases fragment survival.

Reef Restoration Questionnaire.—Seventy-nine coral reef restoration practitioners responded to the questionnaire. The most common participants were individuals associated with academic institutions and private organizations (39.3%), government employees (30.4%), or members of NGOs (18.9%). Other participants identified themselves as members of the dive/tourism/resort industry, volunteers, or marine/environmental consultants and contractors (11.4%). Most respondents (60%) indicated at least 5 yrs of reef restoration experience and 20% indicated 15+ yrs of experience. For most questions, no statistical differences were found between the background of the respondent or the level of experience. Therefore, all responses were combined for analysis except when noted. Respondents were explicitly asked to only rate the reef restoration methods they had tried, thus questions with fewer than five responses prevented us from statistically comparing differences between groups.

When asked about the status and trends of Caribbean *Acropora* populations, 90% and 85% of respondents stated that *A. cervicornis* and *A. palmata* are either degraded or severely degraded, respectively (Fig. 4A). Moreover, the majority of respondents believe wild populations of *A. cervicornis* (55.6%) and *A. palmata* (85.3%) continue to decline, are not recovering naturally, and their threatened status is therefore warranted (Fig. 4B). When asked to rank how important active reef restoration is to the future of coral reefs on a scale from 1 (not important) to 5 (extremely important), respondents indicated active reef restoration was either important or extremely important [mean rank = 3.9 (SD 1.1), median rank = 4]. Moreover, active reef restoration was ranked as either important or extremely important for the future of Caribbean acroporid corals [mean = 4.3 (SD 1.0), median = 5]. Additionally, participants indicated that active coral reef restoration could be an efficient coral reef management

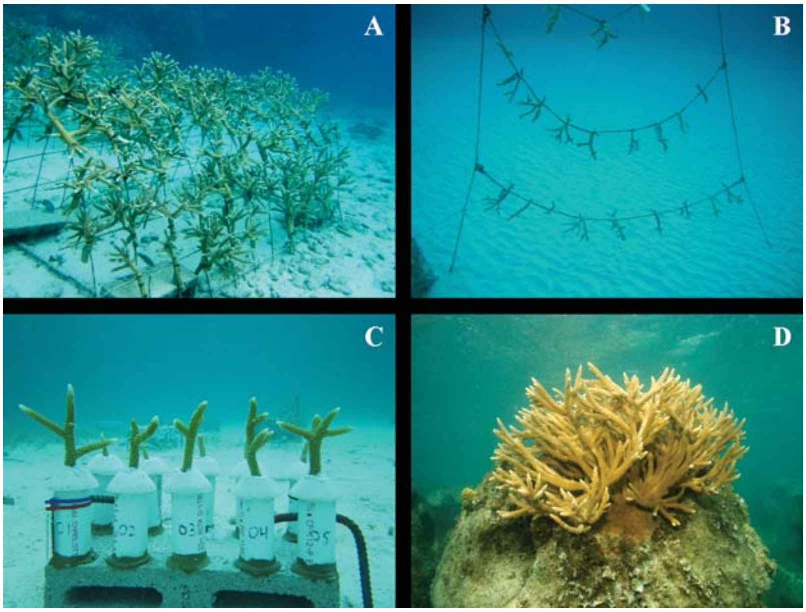

Figure 3. (A) Wire frames, (B) ropes, (C) cinder-block platforms, and (D) Reef Balls used as artificial structures for propagating coral fragments within coral nurseries. Photos courtesy of (A) T Thyberg, (B) V Galvan, and (D) E D'Alessandro.

tool [mean = 3.5 (SD 1.3), median = 4]. Statistical differences between groups were detected in responses to the question of *Acropora* recovery potential without human intervention [mean = 2.5 (SD 1.3), median = 2]. Members of NGOs rated *Acropora* as less likely to recover on its own [mean = 1.5 (SD 0.7), median = 1] than members from academic institutions [mean = 2.5 (SD 1.2), median = 2] or government agencies [mean = 3.3 (SD 1.5), median = 2; one-way ANOVA: $P = 0.008$]. Additionally, respondents with 6–10 yrs of experience [mean = 1.9 (SD 1.0), median = 2] thought *Acropora* is less likely to recover without human intervention than respondents with >15 yrs of experience [mean = 3.3 (SD 1.3), median = 3; one-way ANOVA: $P = 0.024$].

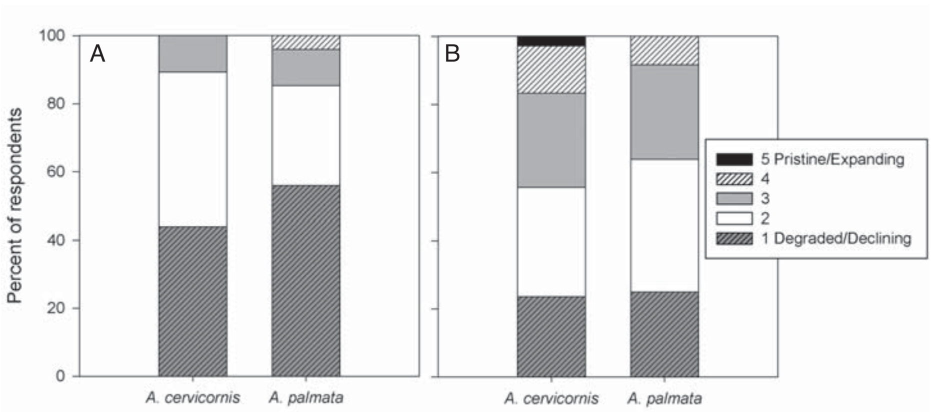

Figure 4. Percentage of respondents that ranked the (A) status and (B) trends of *Acropora palmata* and *Acropora cervicornis* populations as (A) degraded (1) to pristine (5) and (B) declining (1) to expanding (5).

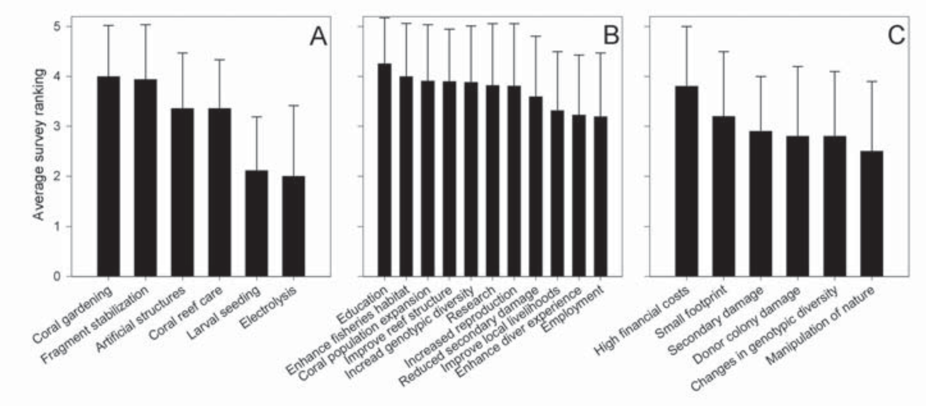

Figure 5. Mean ranking by respondents on (A) the effectiveness of various restoration methods, (B) the potential benefits of reef restoration, and (C) concerns facing coral reef restoration efforts.

The most common restoration methods used by participants were fragment stabilization (practiced by 62.3% of respondents) and coral gardening (practiced by 74.0% of respondents; defined in the questionnaire as coral fragment propagation within nursery environments for use in outplanting). Larval seeding and electrolysis were among the least common methodologies used by participants (19.5% and 1.3%, respectively). Coral gardening [mean = 4.0 (SD 1.0), median = 4] and fragment stabilization [mean = 3.9 (SD 1.0), median = 4] were ranked as the most effective methods of reef restoration (Fig. 5A). In contrast, electrolysis was considered the least effective method [mean = 2.0 (SD 1.4); median rank = 1.5]. Respondents believed that coral gardening and fragment stabilization were significantly more effective than electrolysis, larval seeding, and coral reef care (i.e., fragment stabilization, predator removal, algal weeding, sediment removal; Kruskal-Wallis one-way ANOVA on ranks: H = 48.0. $P < 0.001$; Table 3). The highest-ranked coral reef care method was the rescue of broken colonies and/or coral fragments after disturbance events such as ship groundings and storms [mean = 4.1 (SD 0.9), median = 4].

The highest-ranked outplanting (transplanting nursery-grown corals to the reef) method was securing fragments or colonies to the reef substrate using cement and/or epoxy [mean = 3.8 (SD 1.1), median = 4] or with cable ties and/or wire [mean = 3.5 (SD 1.3), median = 4]. Wedging corals directly into holes and crevices in the reef framework [mean = 2.6 (SD 1.0)], attaching corals to lines, ropes or mesh secured to the substrate [mean = 2.9 (SD 1.2)], or affixing corals to nails driven into the substrate [mean = 3.2 (SD 1.2)] were considered the least effective methods (median = 3 each). The use of cement and/or epoxy and cable ties and/or wire was considered significantly more effective than direct wedging by restoration practitioners (Kruskal-Wallis one-way ANOVA on ranks: H = 30.8, $P = < 0.001$; Table 2).

Among the potential benefits that coral reef restoration can provide, the highest-ranked benefit was increased public awareness and education [mean = 4.3 (SD 0.9), median = 5; Fig. 5B]. Enhanced fisheries habitat [mean = 4.0 (SD 1.1)], increased coral population expansion [mean = 3.9 (SD 1.1)], improved reef structure [mean = 3.9 (SD 1.1)], and increased genotypic diversity [mean = 3.9 (SD 1.1)] were also highly rated as potential benefits of reef restoration (median = 4 each). Overall, these coral reef restoration benefits were ranked significantly higher than the least valuable

Table 3. Mean ranking and significance of the effectiveness, potential benefits, and concerns of coral reef restoration by participants.

Topic	Median ranking	Mean ranking	SD	Kruskal-Wallis test
Effectiveness of coral reef restoration methods				H = 48.0; $P < 0.001$
Coral gardening	4.0	4.0	1.0	
Fragment stabilization	4.0	3.9	1.0	
Artificial structures	4.0	3.4	1.1	
Coral reef care	3.0	3.4	1.0	
Larval seeding	2.0	2.1	1.1	
Electrolysis	1.5	2.0	1.4	
Effectiveness of outplanting methods				H = 30.8; $P < 0.001$
Cement/epoxy	4.0	3.8	1.1	
Cable ties/wire	4.0	3.5	1.3	
Nails	3.0	3.3	1.2	
Wedging	3.0	2.9	1.0	
Line/rope	2.0	2.6	1.2	
Potential benefits of reef restoration				H = 64.6; $P < 0.001$
Education	5.0	4.3	0.9	
Enhance fisheries habitat	4.0	4.0	1.1	
Coral population expansion	4.0	3.9	1.1	
Increase genetic diversity	4.0	3.9	1.1	
Improve reef structure	4.0	3.9	1.1	
Research opportunities	4.0	3.8	1.2	
Increase reproductive output	4.0	3.8	1.2	
Reduce secondary disturbances	4.0	3.6	1.2	
Improve local livelihoods	3.0	3.3	1.2	
Enhance diver/tourist experience	3.0	3.2	1.2	
Employment opportunities	3.0	3.2	1.3	
Coral reef restoration concerns				H = 41.8; $P < 0.001$
High financial cost	4.0	3.7	1.2	
Small footprint	3.0	3.2	1.2	
Changes in genotypic diversity	3.0	2.9	1.3	
Secondary damage	3.0	2.9	1.2	
Damage to donor colonies	3.0	2.8	1.3	
Manipulation of nature	2.0	2.5	1.3	

benefits such as enhanced diver/tourist experience, employment opportunities, and improved local livelihoods (Kruskal-Wallis one-way ANOVA on ranks: H = 64.6, $P \leq 0.001$; Table 3). In addition, 68% of respondents consider MPAs as either important or extremely important to the success of coral restoration projects [mean = 3.9 (SD 1.2), median = 4], indicating the use of MPAs as sites for reef restoration as an important benefit to ensure the success of restoration activities and to improve the survival of *Acropora* populations.

Respondents were also asked to rank a variety of concerns related to reef restoration practices. High financial cost was the biggest concern among participants [mean = 3.7 (SD 1.2), median = 4; Fig. 5C]. The risk of damage to donor colonies, manipulation of nature, and changes in genotypic diversity, however, were ranked significantly lower than high financial costs (Kruskal-Wallis One-Way ANOVA on ranks: H = 41.8; $P \leq 0.001$; Table 3). Finally, 58% of *Acropora* reef restoration practitioners identified "lack of funding" as an obstacle experienced during their projects (Fig. 6). The next most common obstacles were project continuity and lack of project follow-up (33% each) along with government red tape and time constraints (32% each).

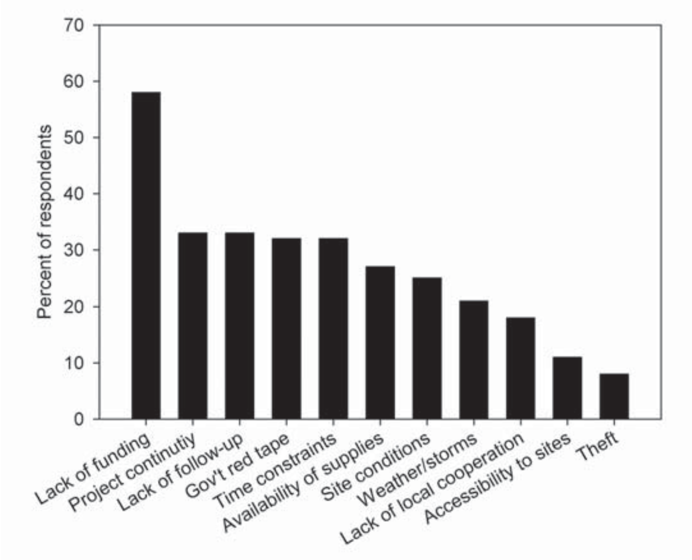

Figure 6. Percentage of respondents indicating common obstacles of Caribbean reef restoration projects.

Discussion

Most recent coral propagation and coral reef restoration activities in the Caribbean have focused on the threatened genus *Acropora* (Bruckner 2002, *Acropora* Biological Review Team 2005). This concentration is mainly due to the historical and continued decline of this important reef-building genus, and the success of projects using *Acropora* for propagation and restoration. One of the most remarkable findings of this review is the agreement among coral reef scientists and managers that active propagation and restoration activities will play an important role in the future recovery of *Acropora*. However, practitioners emphasized the need for active restoration to be conducted in conjunction with robust local and regional management strategies to mitigate the impacts of anthropogenic and natural disturbances such as those associated with global climate change, land-based sources of pollution, habitat destruction, and overfishing. Because reef restoration efforts can prove futile if the initial agent or source of degradation has not been permanently removed from the impacted area (Jaap 2000, Precht 2006), reef restoration must be considered as a complement to management tools that address the larger causes of reef degradation. The need for an integrated approach to coral reef restoration was highlighted in the responses by the suggested importance of conducting coral reef restoration activities within MPAs to provide positive synergisms between coral reef management tools.

In our study, the highest ranked and most effective coral reef propagation and restoration techniques were low-tech methodologies, utilizing inexpensive and readily available materials such as wire mesh, PVC, plastic cable ties, cinder blocks, nails, fishing line, and ropes (Becker and Mueller 2001, Bowden-Kerby 2001, Hernández-Delgado et al. 2001, Quinn et al. 2005, Herlan and Lirman 2008). This indicates that propagation and restoration activities using *Acropora* have the potential to be conducted successfully at low cost. Additionally, it has been shown that these low-tech propagation and restoration activities can be an empowering education tool when integrated into community-based management (Bowden-Kerby 2001). These techniques can be used to assist local coastal communities to restore and manage their own local reef resources. Thus, the integration of socioeconomic needs and perspectives of local stakeholder groups who depend upon coral reefs in the Caribbean is an important step in successful coral reef restoration (Bowden-Kerby 2001, Goreau and Hilbertz 2005). Respondents indicated that project continuity beyond the initial funding cycle will depend on the involvement of local stakeholders outside the scientific and management community. Thus, the adoption of propagation and restoration projects by dive shop operators, resort owners, fishermen, and local communities were identified as key components to the long-term success of restoration programs.

With low-tech, cost-efficient methods, people of coastal communities can conduct restoration activities to restore and protect their local reefs, and therefore promote community-based management of local resources through continued public education and awareness. For example, in Punta Cana, Dominican Republic, an *Acropora* nursery and restoration site has resulted in the establishment of a voluntary marine protected area by local fishermen and has become a popular dive and snorkel site due to the increased biodiversity as a direct result of *Acropora* restoration activities. This project involves partners from NOAA, various NGOs, and the local community and dive operators to maintain and manage the site. Additionally, on the island of Utila in Honduras, the utilization of low-tech and low-cost techniques by local volunteers in partnership with several NGOs and the Honduras Ministry of Tourism has resulted in the enhancement of approximately 500 linear meters of reef with >500 nursery-reared *A. cervicornis* colonies with a 50% survival rate >7 yrs. An extraordinary example of the ability and drive of a local community to drastically increase the quality of their reef ecosystem through the use of inexpensive and easy methodologies comes from Bolinao, Philippines, where up to 1200 m^2 of reef were outplanted by hand by local free-divers wearing handmade plywood flippers (Normile 2009). By involving the local community to participate in coral restoration projects, they can witness their ability to protect and expand the resources upon which they depend for both food and income (Goreau and Hilbertz 2005). Furthermore, reef restoration can be an empowering educational tool to promote public awareness and participation in coral reef conservation, providing the foundation for community-based management and serving as a unification point between sometimes antagonistic stakeholder groups (i.e., government agencies, NGOs, conservationists, fishermen, and the tourism industry; Stepath 2000), which will dramatically improve Caribbean-based reef restoration efforts.

In addition to the cost of propagation and restoration activities, the lack of continued funding, limited project follow-up, and lack of project continuity were highlighted as limitations to the establishment and success of long-term restoration programs in the Caribbean. Restoration activities are often initiated with extramural funding and struggle to continue beyond the initial 1- to 3-yr funding cycle. In many cases, this leads to a paucity of publications and lack of project documentation that has forced practitioners to implement projects with limited prior knowledge. For example, in the Caribbean, only two restoration studies including *Acropora* transplantation and fragment stabilization exist with data exceeding 10 yrs (Bruckner et al. 2009, Garrison and Ward 2012). Hence, the information and sources included here, as well as the recent publication of restoration manuals (Precht 2006, Edwards and

Gomez 2007, Edwards 2010, Johnson et al. 2011), provide collective knowledge and best practices that can aid practitioners in the development of new, scientific-based restoration projects.

Another concern raised by respondents was the potential negative impacts on remaining donor populations and reefs. However, the potential negative impacts to donor populations are only a concern when collecting colonies or fragments from wild populations to stock nurseries or when whole corals are transplanted from healthy to degraded sites. Studies have shown that *Acropora* fragments can be collected without causing significant mortality on donor colonies (Becker and Mueller 2001, Lirman et al. 2010) and that pruning of branching corals, like *A. cervicornis*, actually results in an overall increase in productivity through pruning vigor (Lirman et al. 2010). Additionally, the direct transplantation of corals or fragments from healthy to damaged sites without an intermediate nursery step is rare given the present condition of coral reefs around the world. In fact, transplantation of corals from one site to another is usually only utilized to relocate corals prior to the destruction of a reef site during projects such as dredging, port and marina expansion, or beach renourishment activities (Gayle et al. 2005, Seguin et al. 2010).

While even the largest reef restoration projects pale in comparison to the scale of natural processes during a successful sexual recruitment event, establishing multiple small, genetically diverse populations that will, in time, become sexually reproductive can contribute to species recovery, especially in areas of significant parent population declines (Baums et al. 2005, Vollmer and Palumbi 2007). Therefore, we suggest that by strategically restoring populations to fill spatial gaps in species distribution, small reproductive populations may have the potential to significantly contribute to the overall success of gamete fertilization and sexual recruitment of *Acropora* populations. For example, an estimated 1500 corals from the *Acropora* coral nursery have been outplanted to local reefs by the Coral Restoration Foundation in Key Largo, Florida, and some of these outplanted corals were reported to spawn in 2009 (Nedimeyer, Coral Restoration Foundation, pers comm). In addition, spawning was observed in *A. palmata* fragments 3 yrs after stabilization to reefs near Boca Chica, Dominican Republic (B Bezy, University of Costa Rica, pers comm). These marked the first reported spawning events of restored *Acropora* in the Caribbean.

The concerns expressed by respondents regarding genetic modifications to wild populations include the possibility of establishing monoclonal populations that would reduce fertilization success or artificially increase the local dominance of certain genotypes that may depress the genetic contribution of wild genotypes. In the past, reef restoration and coral propagation activities have not considered genetic or genotypic diversity explicitly, but recent developments in molecular tools have allowed researchers to assess local and regional coral genotypic diversity of wild populations as well as identify and track the performance of genetic lineages within coral nurseries and outplant sites (Baums 2008, Schopmeyer et al. 2011). This information will prove invaluable for use in restoration programs to select appropriate genetic sources and influence the spatial arrangement of transplanted populations.

Perhaps the largest debate surrounding the field of coral reef restoration is whether the risks and costs of restoration activities exceed the benefits and rewards they provide. On an ecological scale, key losses in coral reef biodiversity have devastating consequences on resilience and resistance (Bellwood et al. 2004, Palumbi et al. 2009). The global value of the goods and services provided by coral reefs has been estimated at US$375 billion yr^{-1} (Edwards and Gomez 2007). More specifically, Caribbean reefs have been valued between US$100,000 and US$600,000 km^{-2} of coral reef totaling approximately US$3.1–$4.6 billion annually generated through food production from fisheries (US$310 million), tourism and recreation (US$4.7 billion), and shoreline protection (US$740 million to US$2.2 billion; Burke and Maidens 2004). Thus, the continued degradation of Caribbean reef systems may result in significant economical losses totaling US$350–$870 million annually. Moreover, the socioeconomic importance of reefs in the Caribbean is compounded by the fact that many of these coral reef nations are small, developing island states, where vulnerability is often exacerbated by high coastal population densities, scarce resources, geographic isolation, weak economies, and susceptibility to natural disturbances such as hurricanes, tsunamis, and sea level rise (Burke et al. 2011). Therefore, the potential for biological and economic losses through the complete degradation of Caribbean reefs greatly underscores the need for coral reef protection and restoration, particularly of acroporid corals, which provide the primary foundation of reef structural complexity (Bruckner 2002). The cost of Caribbean coral reef restoration can be high, with simple coral transplantation projects costing US$10,000 ha^{-1} and projects including physical restoration of the reef substrate and framework, such as repairing the reef framework after a ship grounding, costing upwards of US$2.0–$6.5 million ha^{-1} (Spurgeon 2001, Edwards 2010). However, the cost of simple nursery and transplant techniques appears minimal compared to the compounded annual losses of ecosystem goods and services from damaged and degraded reefs.

Based on our literature review and responses, it appears that the future of reef restoration in the Caribbean and western Atlantic relies on two fundamental priorities. First, utilizing low-cost restoration methodologies is crucial to improving the number, length, and success of restoration activities. Second, restoration activities must be conducted in conjunction with ecosystem-based management and conservation practices (i.e., MPAs and no-take zones) to mitigate the impacts of anthropogenic and natural disturbances. Therefore, low-cost and low-tech coral reef propagation and restoration methodologies combined with higher levels of protection and long-term monitoring will act as potential complementary management tools for future rehabilitation of Caribbean reefs, and specifically, the future recovery of threatened Caribbean acroporid coral species. While challenges and obstacles still remain in the field of active coral propagation and reef restoration, an increasing body of knowledge is now available to support these activities and ensure that the benefits of these programs exceed the potential risks to remaining wild coral populations and coral reef communities.

Acknowledgments

This project was funded by Counterpart International and the Frohring Foundation. The questionnaire greatly benefited from comments by A Bowden-Kerby, M Estevanez, and M Shivlani. We appreciate the information graciously provided by the practitioners conducting reef restoration activities as well as the respondents of the online questionnaire. This manuscript benefitted from comments by C Drury, B Huntington, R Santos, and T Thyberg, and GIS assistance was provided by J Blondeau.

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Date Submitted: 21 December, 2011.
Date Accepted: 1 June, 2012.
Available Online: 2 July, 2012.

Address: *University of Miami, Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, Florida 33149-1098.* Corresponding Author: (DL) *Email: <dlirman@rsmas.miami.edu>.*