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Carlos Toledo-Hernández, Claudia P. Ruiz-Diaz, Edwin A. Hernández-Delgado, and Samuel E. Suleimán-Ramos

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Cover Photograph: Images illustrating *Acropora cervcornis* (Staghorn Coral) fragments raised in a nursing unit at Punta Soldado, Culebra, Puerto Rico, Before (left) and after (right) hurricanes Irma and María. Photograph © Clauda Patricia Ruiz-Diaz.

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Devastation of 15-year old Community-based Coral Farming and Reef-restoration Sites in Puerto Rico by Major Hurricanes Irma and María

Carlos Toledo-Hernández[1,*], Claudia P. Ruiz-Diaz[1], Edwin A. Hernández-Delgado[1], and Samuel E. Suleimán-Ramos[1]

Abstract - Category-5 hurricanes Irma and María impacted the northeastern Caribbean in September 2017, with waves in excess of 10 m. Herein, we provide the first assessment of hurricane damage to community-based coral farming and reef restoration at several locations from Culebra Island, Puerto Rico. Hurricanes destroyed 75 coral farms, killing 11,074 *Acropora cervicornis* (Staghorn Coral) fragments. Likewise, over 9000 recently out-planted colonies as well as most of the coral species adjacent to the outplants perished when they were buried by sand and rubble or were dislodged as a result of hurricane-generated waves. *Liagora* spp. (marine red algae) and other red algae rapidly colonized coral rubble and open-reef substrates, threatening surviving corals of multiple species at least for several weeks after hurricane impacts.

Culebra, an island-municipality located 28 km off the east coast of Puerto Rico, supports extensive coral reef ecosystems and is the center of one of most prominent community-based coral-reef–restoration projects in the Caribbean, the Community-Based Coral Aquaculture and Reef Rehabilitation Program, led by Sociedad Ambiente Marino (SAM) (Fig. 1). Since 2003, the clear and relatively oligotrophic waters of Punta Soldado (PSO), Bahía Tamarindo (BTA), and Punta Tamarindo Chico (PTC) have harbored over 200 coral farms of different designs that support 180 fish species and invertebrate aggregators (Fig. 2A, B). Taken together, the farms have nursed and harvested over 60,000 coral fragments of multiple reef-building coral species, primarily *Acropora cervicornis* (Lamark) (Staghorn Coral) and to a lesser extent *A. palmata* (Lamark) (Elkhorn Coral). These farms have also produced minor numbers of fragments of *Orbicella* species-complex (star corals), *Dendrogyra cylindrus* Ehrenberg (Pillar Coral), and *Porites astreoides* Lamark (Mustard Hill Coral), among others. With the exception of the latter, the remaining species are listed as endangered under the International Union for the Conservation of Nature Red List (IUCN 2017). Through this project, 79,667 m^2 of reef across western shores of Culebra Island have been successfully restored (Fig. 1).

Culebra was recently impacted by 2 Category-5 hurricanes: Irma (6 September 2017), with sustained winds of 296 km h^{-1} passing 20 km north of Culebra, and María (20 September 2017), with sustained winds of 280 km h^{-1}, passing 32 km south of Culebra, and directly impacting Puerto Rico. Both hurricanes generated confirmed waves of 9–11 m, with higher swells. The strongest wave action from

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Hurricane Irma occurred from the west and southwest of Culebra. The strongest waves from María came first from the southeast, then from the south and southwest of Culebra. Together, these hurricanes impacted the normally protected leeward reef sites of Culebra. Assessments conducted between both hurricanes, and then 3 weeks after the impact of Hurricane María revealed major damage to Staghorn Coral farming structures across nearly 8 ha of restored coral reefs throughout planted coral colonies, and to wild populations across natural reefs. Before hurricane impacts, PSO, BTA, and PTC supported 75 farms at different depths (i.e., 5–12 m), harboring a total of 11,300 Staghorn Coral fragments (Fig. 1). None of the farms survived, and 98% of the fragments perished because they were buried by sand (Fig. 2C, D). Surviving fragments were mainly located in farms installed at greater depths and showed neither bleaching nor disease signs. Of the nearly 9000 Staghorn Coral fragments out-planted over the last 2–3 y at depths ranging from 1 m to 5m (Fig. 3A, B), ~1% survived the hurricane impacts. Most of these fragments were either buried in 10–15 cm of sand (Fig. 3C, D), while others were fragmented or dislodged by extreme wave action. Likewise, nearly 4 out of every 5 small to relatively large, naturally occurring coral colonies of different species (including Staghorn Coral) were either buried in sand due to significant sediment

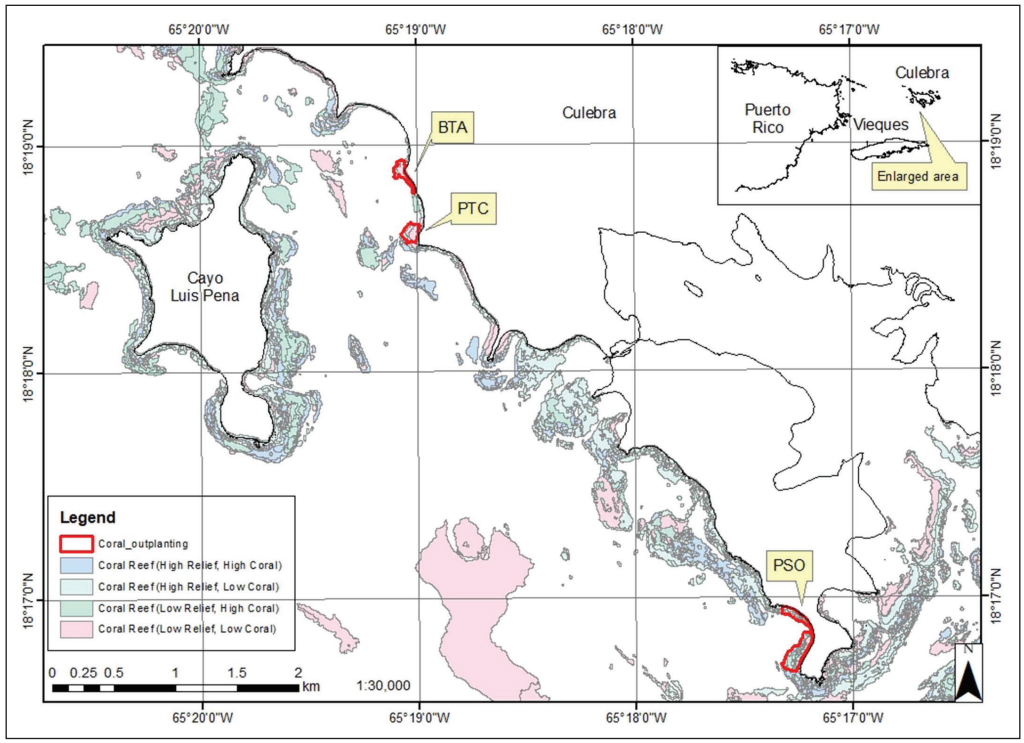

Figure 1. Map of the southwestern coast of Culebra Island indicating the out-planting and coral-farm sites, in addition to the coral cover prior to hurricanes Irma and María impacts. Out-planting sites and coral farms are indicated by the red lines at Bahía Tamarindo (BTA), Punta Tamarindo Chico (PTC), and Punta Soldado (PSO). Map modified from Kågesten et al. (2015).

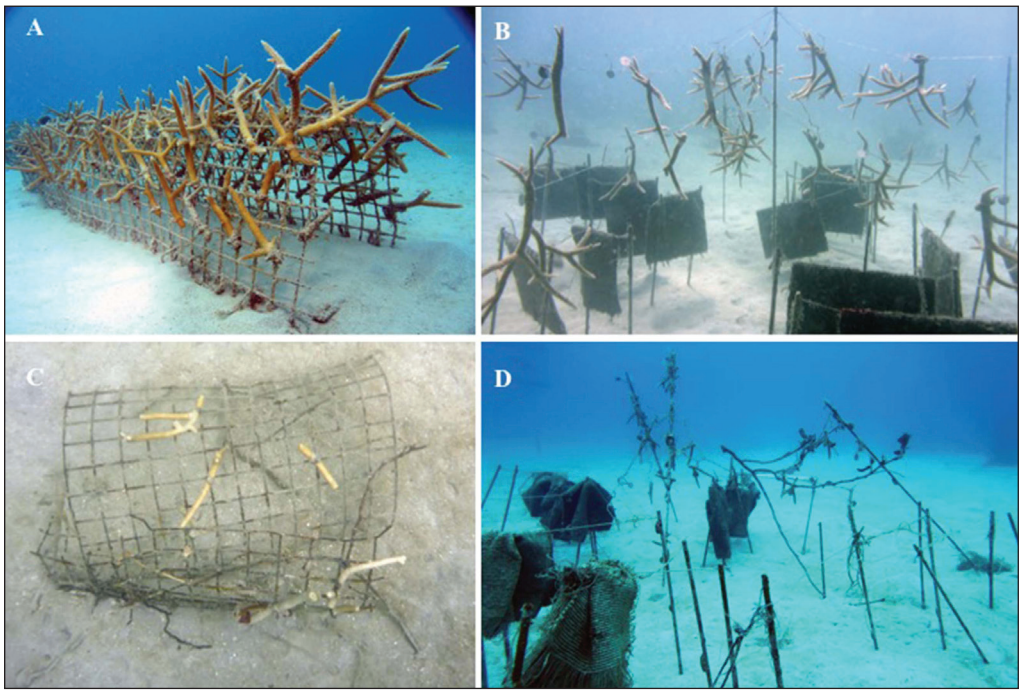

Figure 2. Farms of different designs (A and B) before and (C and D) after hurricane impacts.

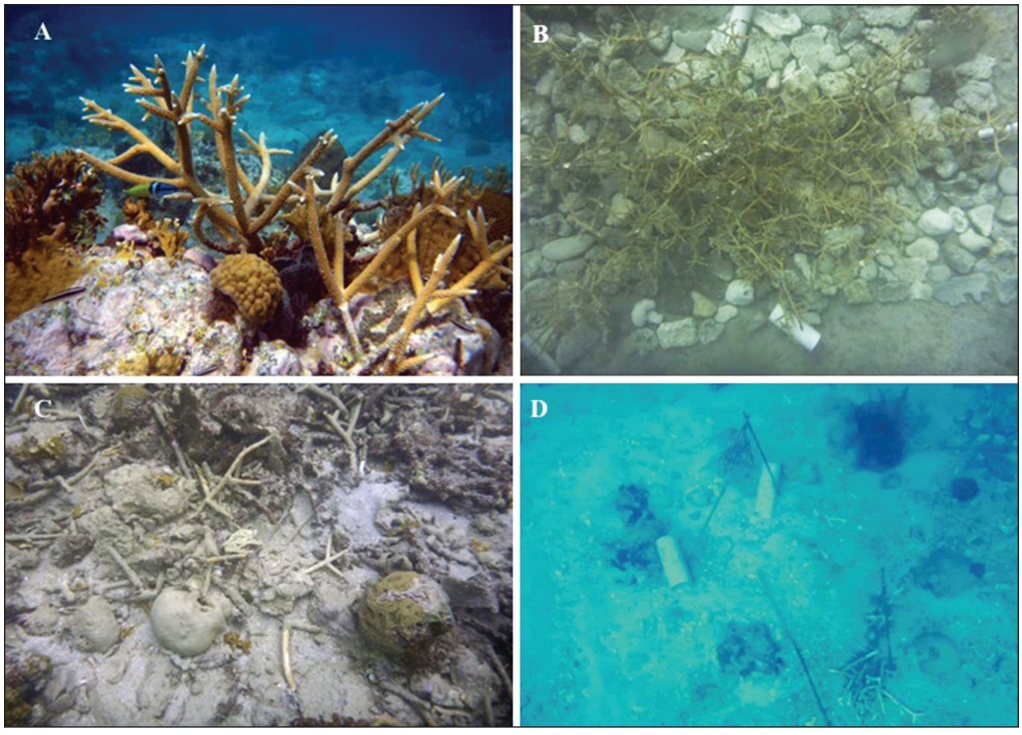

Figure 3. Images showing out-planted Staghorn Coral colonies (A an B) before and (C and D) after hurricanes impacts. B–D are of the same 15-m^2 Staghorn Coral thicket .

bedload or overturned (Fig. 4). Overall, several hectares of natural reef bottom were completely buried and suffocated under extensive coral-rubble fields generated during the hurricanes. This situation has created a major long-term threat to adjacent naturally occurring colonies because future hurricanes may move rubble

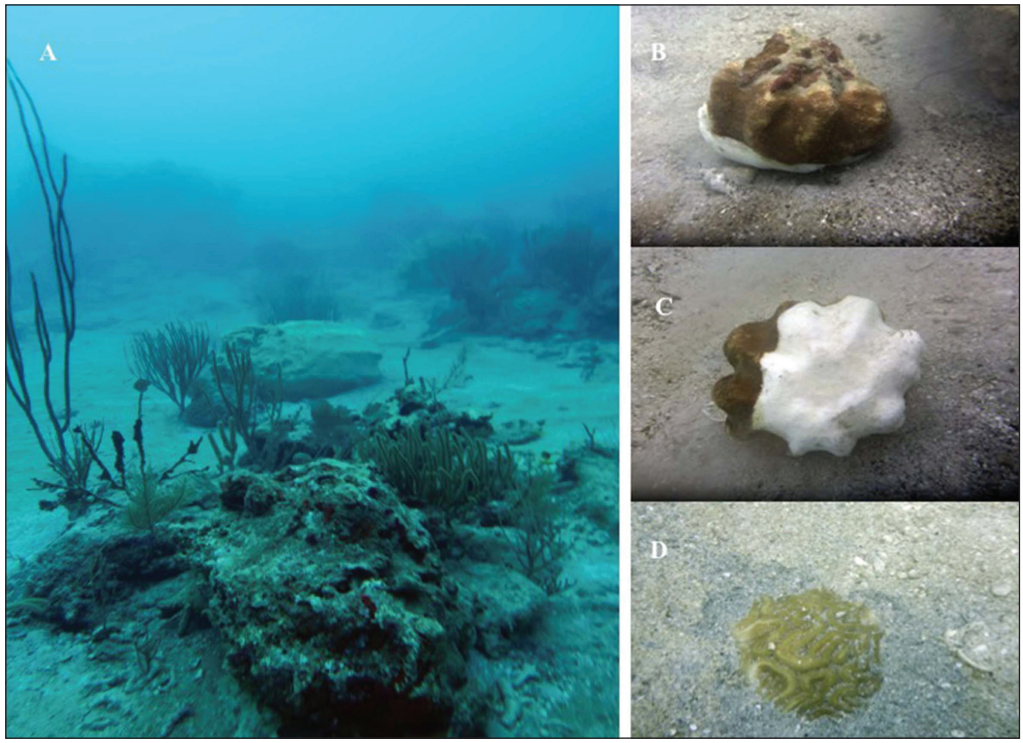

Figure 4. Images illustrating the general damage to the reef. (A) An *Orbicella* spp. coral colony overturned at the background of the image, (B) an *Orbicella franksi (*Gregory) (Boulder Star Coral) colony dislodged and overturned, and (C) the colony rotated to its original growing position. Notice the recently dead area which faced the sandy bottom while overturned. (D) A *Diploria labyrinthiformis* (L.) (Grooved Brain Coral) colony almost completely buried under shifted sand.

Figure 5. Images showing invasion of *Liagora* spp. (A) *Liagora* spp. overgrowing Staghorn Coral rubble and (B) on a juvenile Pillar Coral colony.

fields into deeper reef-habitats, thus affecting remnant Staghorn Coral stands. It is important to note that past hurricane impacts to coral farms in Culebra Island caused minimal mechanical destruction, and most of the observed coral mortality was attributed to extreme rainfall (Hernández-Delgado et al. 2014). Therefore, observed physical destruction of rehabilitated reef bottoms and shallow wild-coral populations is unprecedented.

Both out-planted and naturally occurring colonies that survived the hurricane impacts were further threatened by an extensive algal bloom dominated by red algae, primarily from the genus *Liagora* (Fig. 5). Blooming algae resulted from the combined impact of sediment-laden, nutrient-loaded runoff during the hurricane, and from localized upwelling and sediment resuspension associated with bottom disturbance caused by hurricane waves. It resulted in significant smothering of remnant coral living tissues, and in localized partial colony-bleaching and partial mortality, particularly in small-sized colonies of multiple species. Previous studies have also reported horizontal sediment transport across the seafloor (bedload) and substrate failure due to hurricane-generated waves as main causes of coral mortality (Yoshioka and Yoshioka 1987, 1989; Lugo-Fernández et al. 1994). Likewise, algal blooms have been highlighted as a major cause of coral mortality and recruitment failure after major environmental perturbations such as typhoons (Doropoulos et al 2008).

Given the extensive damage by Hurricanes Irma and María, concomitant with the projected increase in hurricane frequency and/or severity with predicted climate-change effects (Hoegh-Guldberg and Bruno 2010), the natural ability of reefs to recover may become much slower, which may result in a permanent phase shift towards novel states dominated by non-reef–building taxa. Consequently, coral farming and reef-restoration efforts are critical tools to accelerate the recovery. Improved structural designs such as coral nursery farms and the implementation of demographic studies of nursed fragments (i.e., growth and ramifying rates of nursed fragments) can enhance reef-rehabilitation and help to reduce the impacts of hurricanes (Hernández-Delgado et al. 2018a, b). Likewise, there is an imperative need to increase the spatial scale of reef-restoration efforts to expand restored populations to buffer future hurricane impacts.

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