Response to Physical Impacts on Coral Reefs in Puerto Rico and the USVI

2022 Report

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Figure 1: S/V Ef Dia sunk on the reef on left and *Acropora palmata* coral broken during Hurricane Fiona on right (Photo credits: PR DNER on left; Sea Ventures Marine Response Unit on right)

In 2022, the NOAA's Restoration Center (RC) received reports of 36 incidents in Puerto Rico and the US Virgin Islands including Hurricane Fiona, which caused extensive damage to Elkhorn coral, *Acropora palmata,* off the west and southwest coast of Puerto Rico (Appendix I). Emergency restoration conducted at 10 different sites in 2022 saved over 5,000 corals. Since 2006, the RC performed restoration at 152 sites in PR and the USVI and reattached over 67,000 corals (Table 1). National Fish and Wildlife Fund's (NFWF) Coral Emergency Restoration Fund (CERF) funded some of the post Hurricane Fiona restoration work and provided emergency funds to remove a derelict vessel from the reef just before Hurricane Fiona hit which would have caused significant additional damage to the reef.

Response to physical impacts is a Jurisdictional Priority in both PR/USVI, an identified capacity gap in both jurisdictions, and a priority element of the draft Acropora recovery plan. Puerto Rico and the USVI have acknowledged that because of internal limitations and the need for quick and flexible response that more robust action on the part of NOAA was necessary to help stem the unchecked and unnecessary coral losses that were occurring after physical impacts.

In 2009, an emergency response support contract with a local firm Sea Ventures Marine Response Unit was set up. This in combination with the RC's on-the-ground presence in the region has enabled NOAA to address the numerous impacts that were occurring annually. The support contract provides NOAA, PR DNER, and USVI DPNR support to have a functional emergency restoration. A notification network along with a form to report grounding incidents has been set up with the US Coast Guard, salvers, and the local communities. This notification system allows us to get personnel onsite rapidly sometimes while the vessel is still aground on the reef. In many of these cases, our team has been able to provide feedback

to the salvers to minimize further impacts during vessel extractions, saving countless corals. On multiple occasions, we found that the salvers preferred extraction path would have resulted in significant additional damage and on more than one occasion prevented destruction of large thickets of *Acropora spp.*

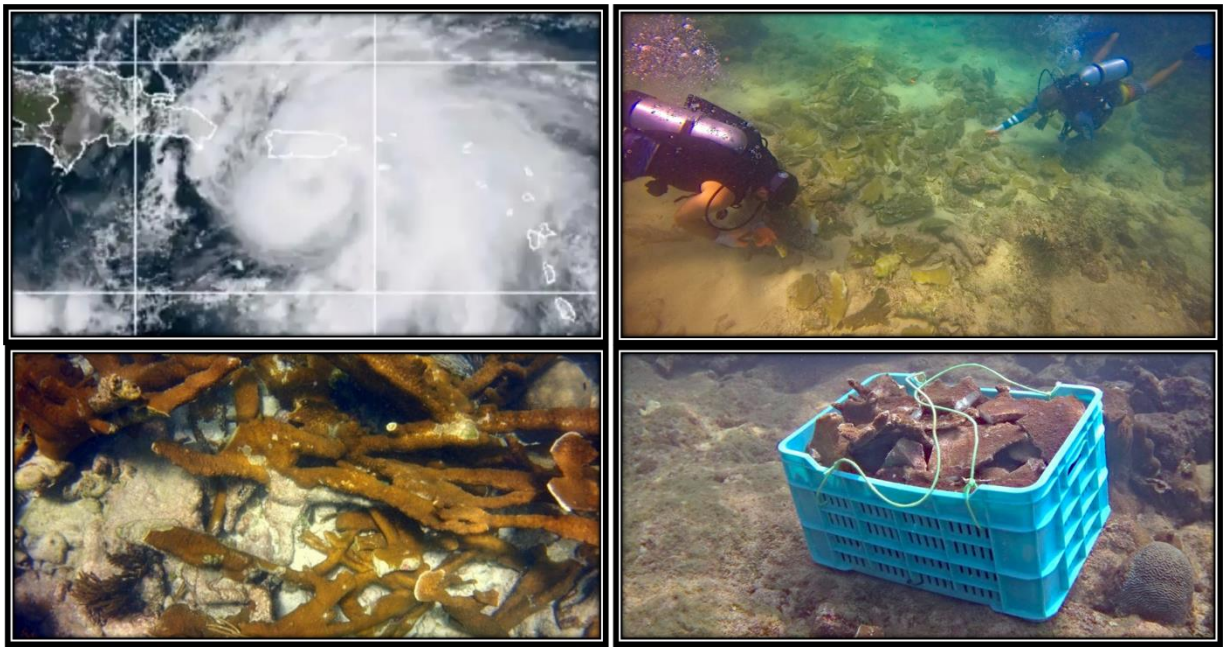
NOAA's Restoration Center, Coral Reef Conservation Program, Protected Resources Division, Assessment and Restoration Division, and the South East Regional Office provided funding for this work. In addition to physical impact response, the support contract serves as a vehicle for funding additional restoration, research and monitoring activities in the region. In some cases, we secured additional funds by engaging federal agencies, private parties and insurance companies to pay for the cost of emergency restoration at multiple sites. This was only possible because we had a previously approved contract set up with a local contractor like Sea Ventures Marine Response Unit who already had the permits to conduct this work and the capability to do immediate post-impact site assessments and restoration. Even with all of the restoration work completed during 2022, there was not enough funding to address all of the reported impacts. For example, NOAA RC and NFWF's CERF provided approximately $500,000 in federal funding for the post Hurricane Fiona work, but this was not enough to address all of the damages. Thousands of at-risk *A. palmata* fragments were still present along with loose rubble created by the storm. It is important to secure them to prevent additional impacts and promote successful coral recruitment needed for reef recovery.

Table 1: Summary of NOAA RC grounding response activities since 2006. * In 2014, an additional 8 Caribbean coral species were included as Threatened on the ESA list.

Year	Total # of Incidents Reported	On-Site Confirmation	Restoration Implemented	# Corals Reattached	% of Restored Sites with Acropora/ ESA Impacts *
2006	1		1	10,500	
2008	1		1	850	
2009	51	25%	7	9,074	43%
2010	32	47%	3	1,045	33%
2011	55	75%	7	915	57%
2012	36	50%	4	2,835	50%
2013	32	31%	3	214	100%
2014	42	48%	12	2,132	67%
2015	51	33%	3	1,919	100%
2016	57	46%	5	8,122	80%
2017	1,080	98%	44	10,552	100%
2018	35	37%	36	9,753	100%
2019	56	27%	2	140	100%
2020	23	13%	1	1,336	100%
2021	28	39%	3	2,360	100%
2022	36	39%	10	5,369	100%
Total or Average Percent	**1,616**	**43%**	**152**	**67,704**	**81%**

Appendix I

Post Hurricane Fiona Coral Restoration Final Report



March 2023

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Executive Summary

Hurricane Fiona significantly impacted on Puerto Rico's coral reefs. Surveys conducted after the hurricane revealed extensive reef damage along the west and south coasts of Puerto Rico. Sites were chosen for restoration based on previous knowledge of the areas, maximum depth and information after surveys. A total of 4,250 *Acropora palmata* fragments were attached with a size range of 20-60 cm of maximum diameter average by Sea Ventures and 1,750 with a size range of 17-28 cm by HJR Reefscaping, for a total of 6,000 *A. palmata* fragments attached. In some areas of restored reefs, photogrammetric analysis were generated for future monitoring of the rescued coral fragments. Also, in some plots rubble stabilization was conducted to mitigate future impacts to outplanted corals caused by rubble movement. Funding for this work was provided by National Fish and Wildlife Fund's (NFWF) Coral Emergency Restoration Fund, and the National Oceanographic and Atmospheric Agency Restoration Center's (NOAA RC) settlement funds from the 2009 LNG-C Matthew grounding. However, there are still thousands of *A. palmata* fragments from this event that are still loose and at risk of dying creating another problem like loose rubble. Additional funding is needed to continue monitoring and stabilizing rubble in restored areas since most of the fragments don't attach well or attach to unstable substrate that do not provide long-term survival. This is key to the output of the implemented triage efforts.

Introduction

On September 18, 2022, category 1 Hurricane Fiona made landfall in southwestern Puerto Rico with up to 110mph wind gusts, 2.5ft storm surge, and up to 20ft groundswell (NOAA Hurricane Center and CariCOOS, 2022). Weeks after the storm, scientific divers and coral reef technicians divers composed of personnel from Sea Ventures, HJR Reefscaping, and The Puerto Rico Department of Natural and Environmental Resources (PR-DNER) conducted surveys to assess the effects of Hurricane Fiona on coral reefs in different parts of south and western Puerto Rico.

Preliminary surveys have focused on 4 areas with special interest to restoration activities due to presence of abundant ESA coral populations, coral nurseries maintained by Sea Ventures and partners, and outplanting sites. These include coastal áreas off Guayanilla, Guánica, Lajas, Cabo Rojo, and Rincón. In these 4 areas a total of 12 reef sites were visited to assess the impacts of Hurricane Fiona and prioritize triage efforts (Figure 1).

Thousands of at-risk *Acropora palmata* fragments were observed at Guanica, La Parguera, Rincon and Cabo Rojo sites and hundreds of these at-risk fragments generated by the swells from Hurricane Fiona were attached. A few entire colonies of *A. palmata* that detached were reattached as well. This report presents a summary of restoration work at priority sites (Cayo Coral, Cayo Aurora, Cayo Laurel, Tres Palmas and El Negro).

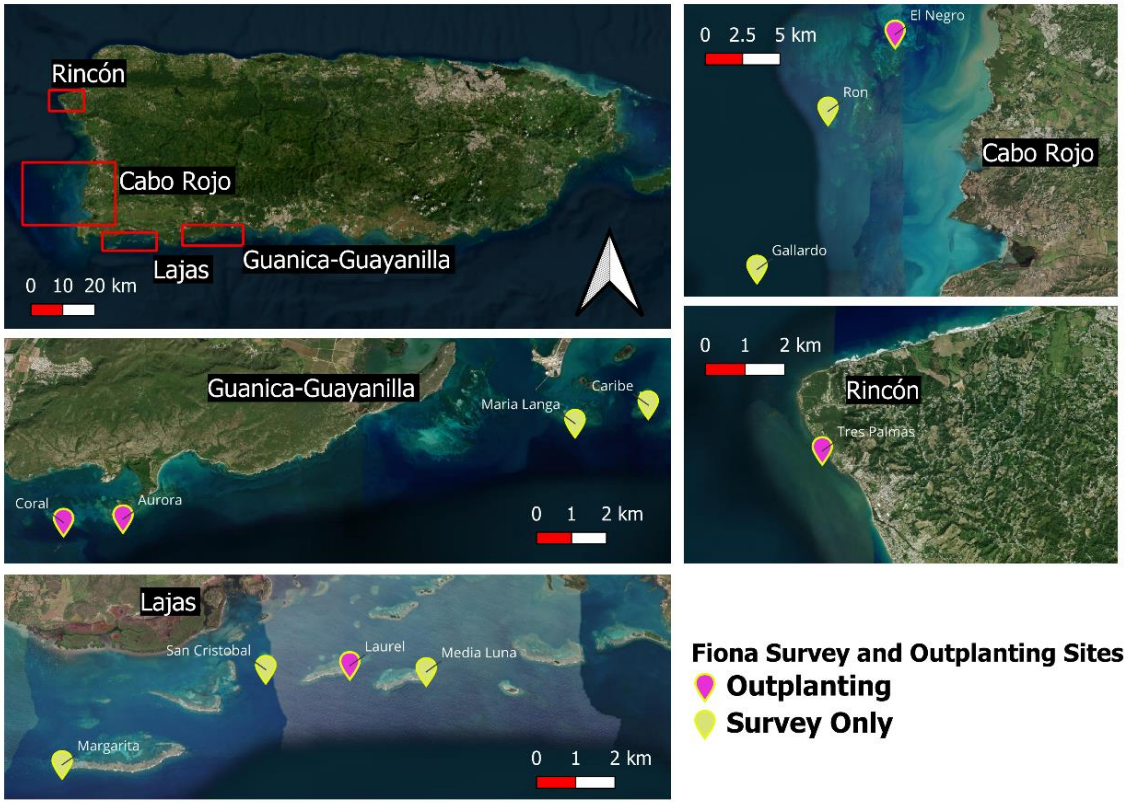


Figure 1*. Geographic areas and sites where preliminary Fiona damage assessments and triage outplanting were conducted.*

Methods

Damage recognition surveys

A damage assessment surveys were conducted at 12 high value shallow (<7m) coral reef sites after the passage of Hurricane Fiona in the southwest coast of Puerto Rico (Table 1), from Guayanilla to Rincón. Most of the damage observed was concentrated in *A. palmata* zone in shallow waters of each site, with thousands of fragments available to cement on the seafloor (Appendix 1: photo 1). Assessments consisted of roving dives to recognize areas with higher density of opportunity fragments that landed in unfavorable substrates for natural reattachment such as sand and unstable rubble. With this information a collaborative effort was planned between the NOAA Restoration Center (NOAA RC), PR- Department of Natural and Environmental Resources (PR-DNER), HJR Reefscaping, and Sea Ventures MRU and successfully implemented by highly experienced and capable dive teams (scientists and trained staff) to triage at-risk corals. From the 12 surveyed sites, 5 sites were prioritized for triage outplanting.

Table 1. *Coordinates to coral reef sites surveyed.*

Site	Latitude	Longitude
Caribe	17.968676	-66.731398
Maria Langa	17.963696	-66.751119
Aurora	17.937968	-66.873004
Cayo Coral	17.937034	-66.889026
Media Luna	17.941020	-67.039366
Laurel	17.942516	-67.057751
San Cristobal	17.941569	-67.077986
Margarita	17.918677	-67.126967
Gallardo	18.003229	-67.330401
Ron	18.103198	-67.285457
El Negro	18.15183	-67.24302
Tres Palmas	18.34924	-67.26514

Acropora palmata triage

Fragments of opportunity were collected at four sites: Cayo Aurora and Cayo Laurel, El Negro and Tres Palmas. Fragments from Cayo Aurora, where extensive *A. palmata* thicket occur, were stored in containers with sea water flow and transported to a

nearby reef (1km away), Cayo Coral, for stabilization. The transport to Cayo Coral was made to enhance *A. palmata* populations at this reef site, in areas where adequate substrate is present, there is minimal coverage of rubble material that can become projectiles in future storms, and where previous restoration efforts have shown high survival of outplants (NOAA RC, Sea Ventures MRU). Fragments were stabilized at the site of collection (in situ) at Cayo Aurora, Cayo Laurel, El Negro and Tres Palmas following recommendations from the PR-DNER partners.

To reattach overturned colonies and fragments generated by Fiona, a mixture of cement with marble sand/powder was used. This mixture was prepared in the Sea Ventures and HJR Reefscaping vessel with seawater. For the mixture to have the necessary consistency, a drill was used to help the components (cement, marble and water) mix properly, all this was done inside buckets that facilitated the transportation of the mixture to the reef (*Figure 2*). The buckets were lowered into the water by means of ropes and then they were transported by coral restoration technical divers to the place where the corals were attached. To move large, overturned colonies to adequate substrate for stabilization lift bags were used (*Figure 3*)

Figure 2. *Cement cargo and mixing process aboard to Sea Ventures Marine Response Unit vessel.*

Figure 3. *Lift bags used to move large, overturned colonies at Cayo Laurel*

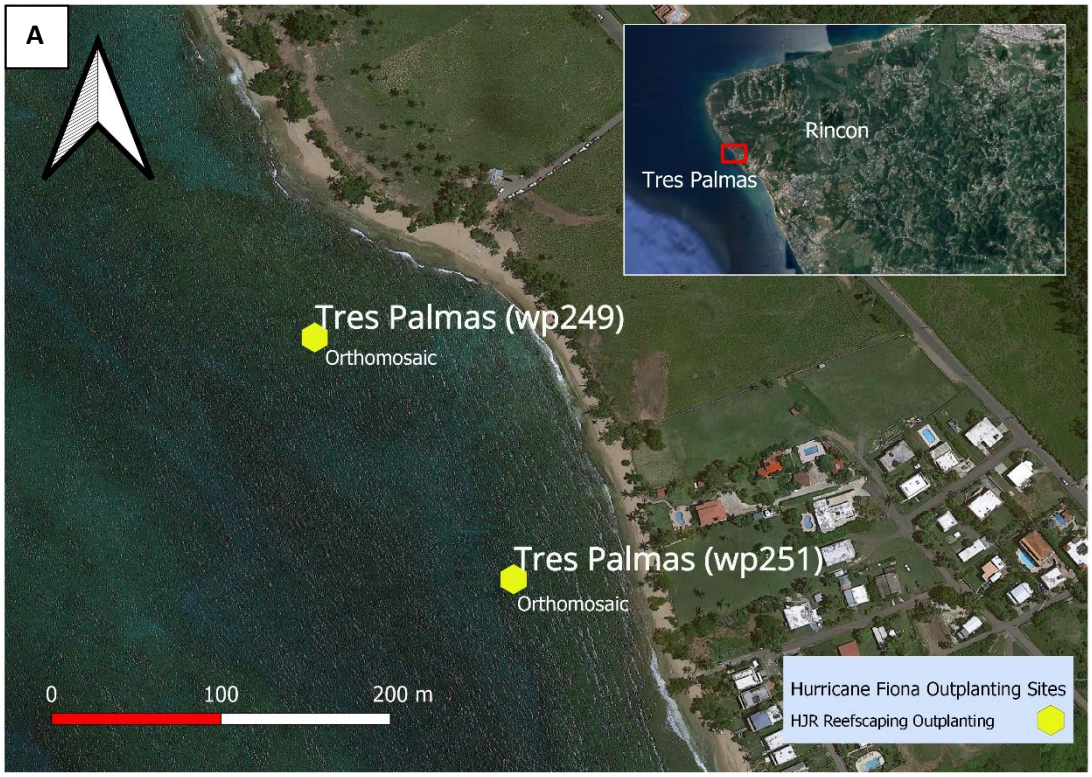
To select the spaces where the corals attach, divers consider benthic cover composition to find areas with reduced presence of competitive macro and turf algal mats, excavating sponges such as the genus *Cliona*, and sand. In addition, it is sought that the substrate is stable, with presence of crustose coralline algae (CCA), and in the case of unstable substrates with rubble they must be stabilized with the cement mix since it must be ensured that the corals do not break off easily with the waves.

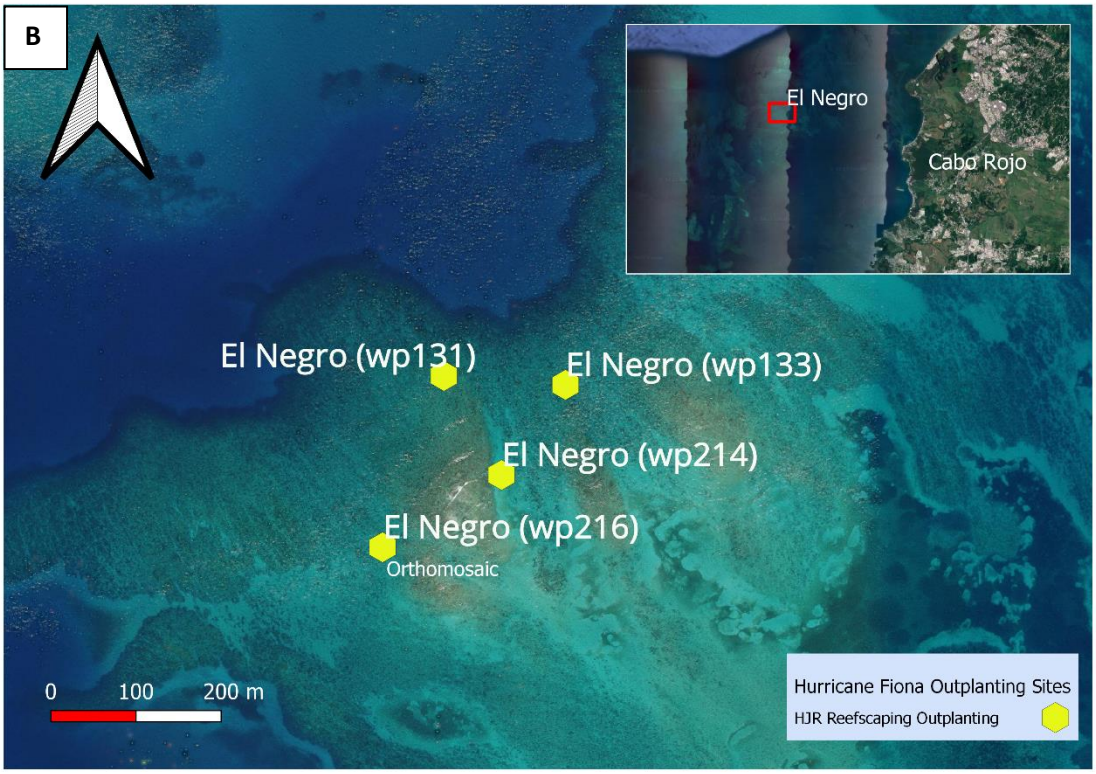
Monitoring and georeferencing

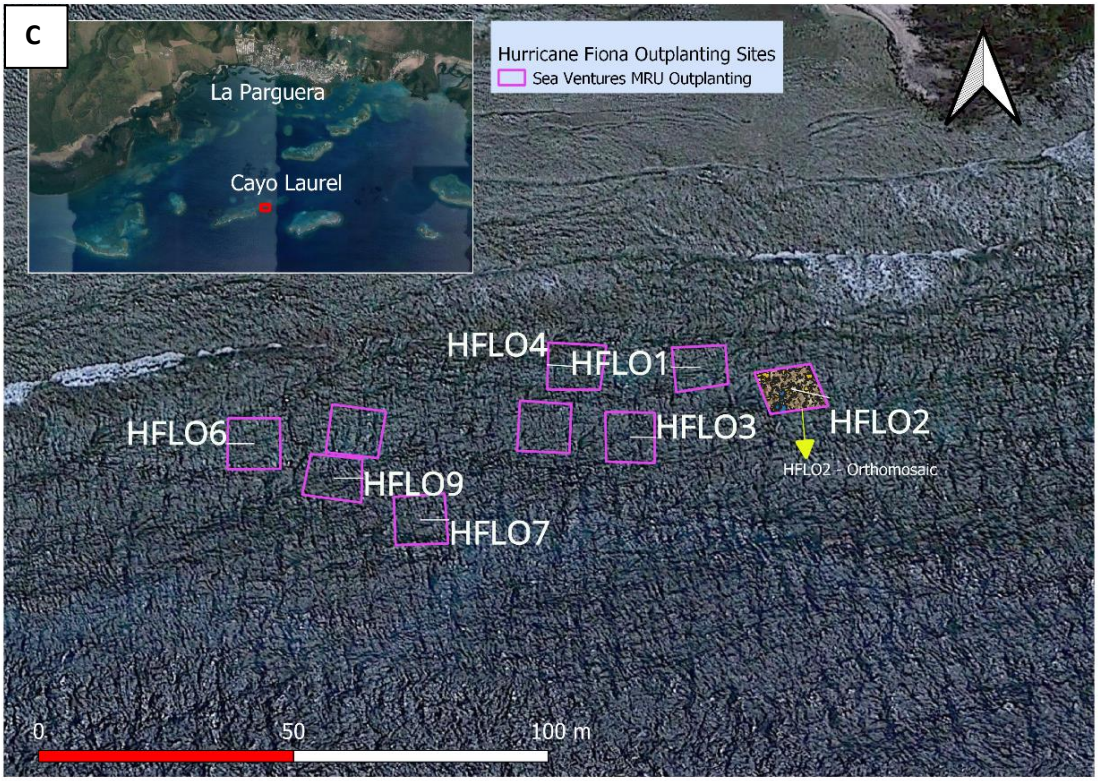
To estimate the restoration footprint and facilitate future monitoring, corals were attached in 10 x 10m plots when possible at Cayo Coral, Cayo Aurora, Laurel, and El Negro, and 5 x 5m plots at Tres Palmas. No plots were established in triage sites where triage was conducted over a broad area. For all plots a GPS central coordinate is taken and 4 additional coordinates for each corner. For plots selected for future monitoring fiberglass rebars are permanently installed. A numeric tag is installed in the center or at one of the corners of the plots. These GPS points are used to update site maps (Figure 4 A,B,C,D,E) and develop a georeferenced database of the project. The number of

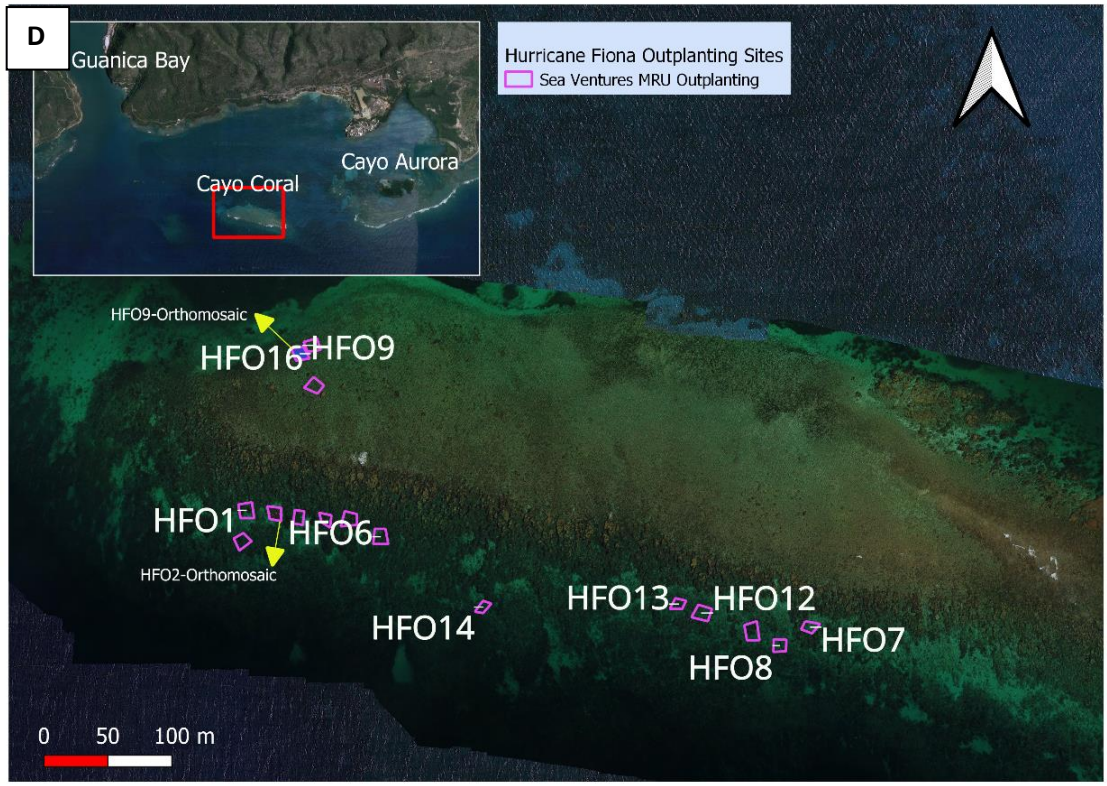
fragments outplanted per plot are counted by a designated coral restoration technician diver every fieldtrip and tabulated.

To create a visual representation of each site and quantify variables related to the success of the restoration (fragments area, cover %, survival %), a subset of plots were selected for photogrammetry analyses. Each photogrammetry plot was photographed completely using high-resolution cameras depending. Photos were imported into Agisoft Metashape Pro software to build orthomosaics and 3D models for visualization of plot benthic structure (Appendix I). Exported orthomosaics were analyzed in artificial intelligence-assisted software TagLab to quantify the abundance (number of colonies and cover %) and size (2D planar area) of *A. palmata* fragments and other benthic components important for the survivorship and growth of outplanted corals such as *Cliona* sponges and rubble areas. Annotations in orthomosaic .tiff files were exported as shapefiles for further visualization in QGIS mapping software (*Figure 5*).




B
El Negro
Cabo Rojo
El Negro (wp131)
El Negro (wp133)
El Negro (wp214)
El Negro (wp216)
Orthomosaic
0
100
200 m
Hurricane Fiona Outplanting Sites
HJR Reefscaping Outplanting


C
La Parguera
Cayo Laurel
Hurricane Fiona Outplanting Sites
Sea Ventures MRU Outplanting
HFLO4
HFLO1
HFLO6
HFLO3
HFLO2
HFLO2 - Orthomosaic
HFLO9
HFLO7
0
50
100 m



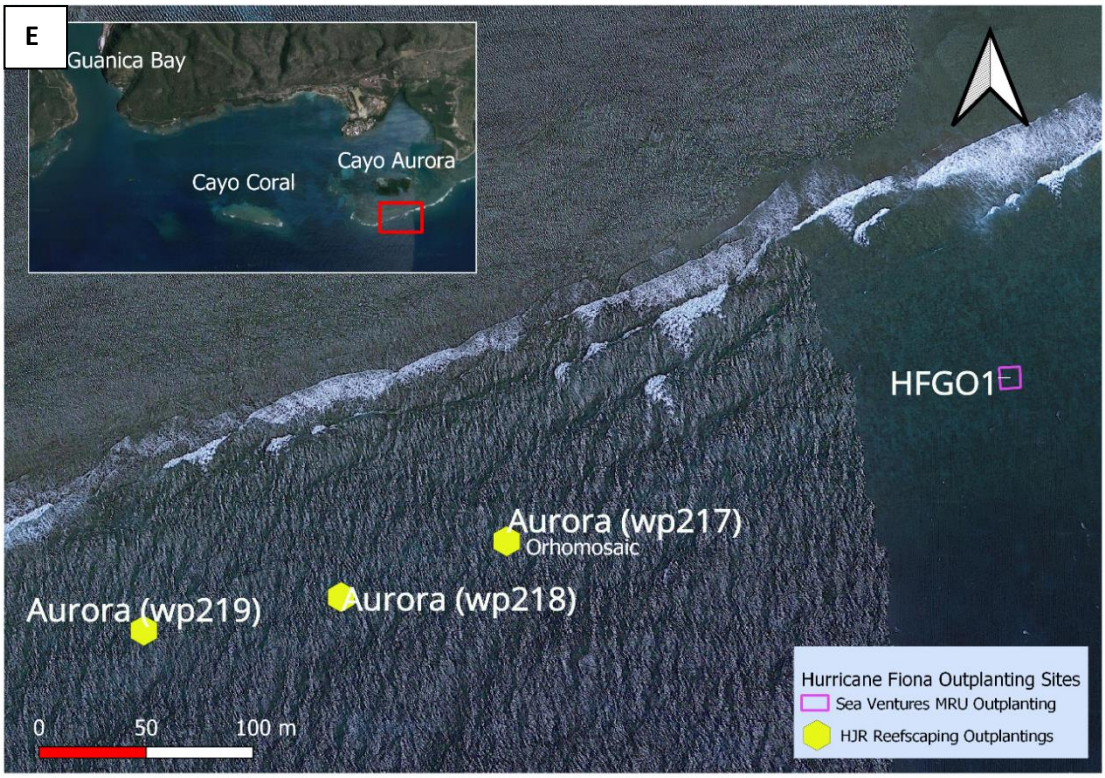


Figure 4. *Triage site maps and plot areas for Tres Palmas (A), El Negro (B), Cayo Laurel (C), Cayo Coral (D) and Cayo Aurora (E). HFO= Hurricane Fiona Outplating, HFLO= Hurricane Fiona Laurel Outplating, HFGO= Hurricane Fiona Guilligan Outplanting*

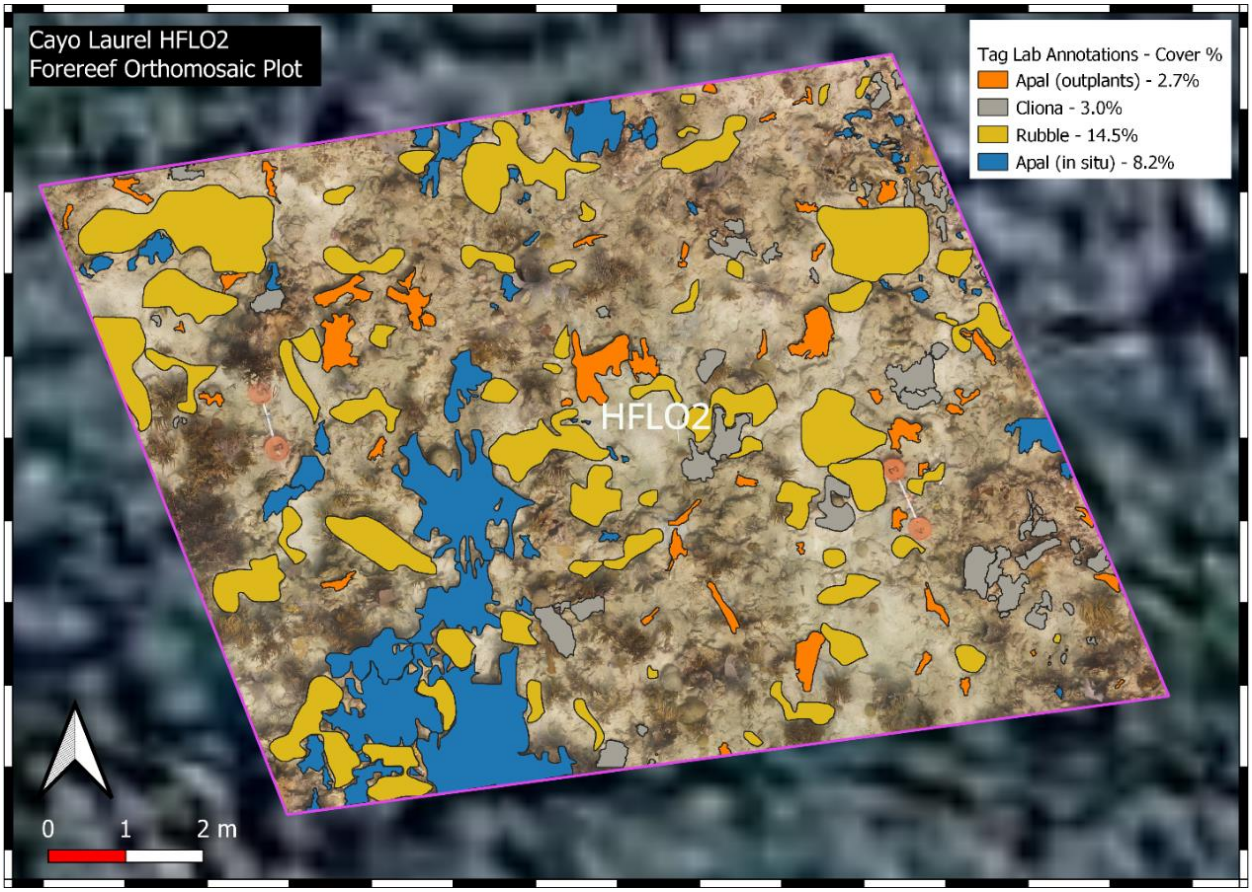


Figure 5*. Example of annotated and georeferenced orthomosaic from plot HFLO2 (Hurricane Fiona Laurel Outplating, plot 2) at Cayo Laurel in-situ triage site by Sea Ventures.*

Results and discussion

Every field workday plots has been completed with an average of 166 *A. palmata* fragments for plot (*Table 2*). A total of 4,250 *A. palmata* fragments were attached with a size range of 20-60 cm of maximum diameter average by Sea Ventures and 1,750 with a size range of 17-28 cm by HJR Reefscaping (*Table 2, Figure 6*) and 96 entire massive colonies reattached with 70 to 265 cm of size range average at Cayo Laurel and Cayo Coral by Sea Ventures (*Table 2, Figure 7*). In some plots rubble stabilization was conducted to mitigate future impacts to outplanted corals caused by rubble movement (*Table 2*, Figure 8,9).

***Table 2**. Metadata for sites and plots. HFO= Hurricane Fiona Outplating, HFLO= Hurricane Fiona Laurel Outplating, HFGO= Hurricane Fiona Guilligan Outplanting*

Plot	Site	# Frags	# Entire Colonies	Rubble Stabilization	Contractor	Funding Agency
HFO1	Cayo Coral	200			Sea Ventures	NOAA
HFO2	Cayo Coral	238			Sea Ventures	NOAA
HFO3	Cayo Coral	204			Sea Ventures	NOAA
HFO4	Cayo Coral	233			Sea Ventures	NOAA
HFO5	Cayo Coral	200			Sea Ventures	NOAA
HFO6	Cayo Coral	204			Sea Ventures	NOAA
HFO7	Cayo Coral	156			Sea Ventures	NOAA
HFO8	Cayo Coral	147			Sea Ventures	NFWF
HFO9	Cayo Coral	157	15	Complete	Sea Ventures	NFWF
HFO10	Cayo Coral	187			Sea Ventures	NFWF
HFO11	Cayo Coral	260		Complete	Sea Ventures	NFWF
HFO12	Cayo Coral	212			Sea Ventures	NOAA
HFO13	Cayo Coral	187			Sea Ventures	NOAA
HFO14	Cayo Coral	165			Sea Ventures	NOAA
HFO15	Cayo Coral	214			Sea Ventures	NOAA
HFO16	Cayo Coral	87		Complete	Sea Ventures	NFWF
HFLO1	Laurel	133	3		Sea Ventures	NFWF
HFLO2	Laurel	146	1		Sea Ventures	NFWF
HFLO3	Laurel	122	10		Sea Ventures	NFWF
HFLO4	Laurel	130			Sea Ventures	NFWF
HFLO5	Laurel	87	3	Complete	Sea Ventures	NFWF
HFLO6	Laurel	85	3	Complete	Sea Ventures	NFWF
HFLO7	Laurel	90	3		Sea Ventures	NFWF
HFLO8	Laurel	139	6		Sea Ventures	NFWF
HFLO9	Laurel	66	52	Complete	Sea Ventures	NOAA
Wp249	Tres Palmas	100			HJReefscaping	NFWF
Wp251	Tres Palmas	140			HJReefscaping	NFWF
Wp214	El Negro	145			HJReefscaping	NFWF
Wp216	El Negro	155			HJReefscaping	NFWF
Wp131	El Negro	260			HJReefscaping	NFWF
Wp133	El Negro	240			HJReefscaping	NFWF
Wp217	Aurora	230			HJReefscaping	NFWF
Wp218	Aurora	238			HJReefscaping	NFWF
Wp219	Aurora	242			HJReefscaping	NFWF
HFG01	Aurora	201			Sea Ventures	NOAA
TOTAL Sea Ventures		**4,250**	**96**			
TOTAL HJR Reefscaping		**1,750**				

***Figure 6**. A. palmata fragments attached at Cayo Laurel*

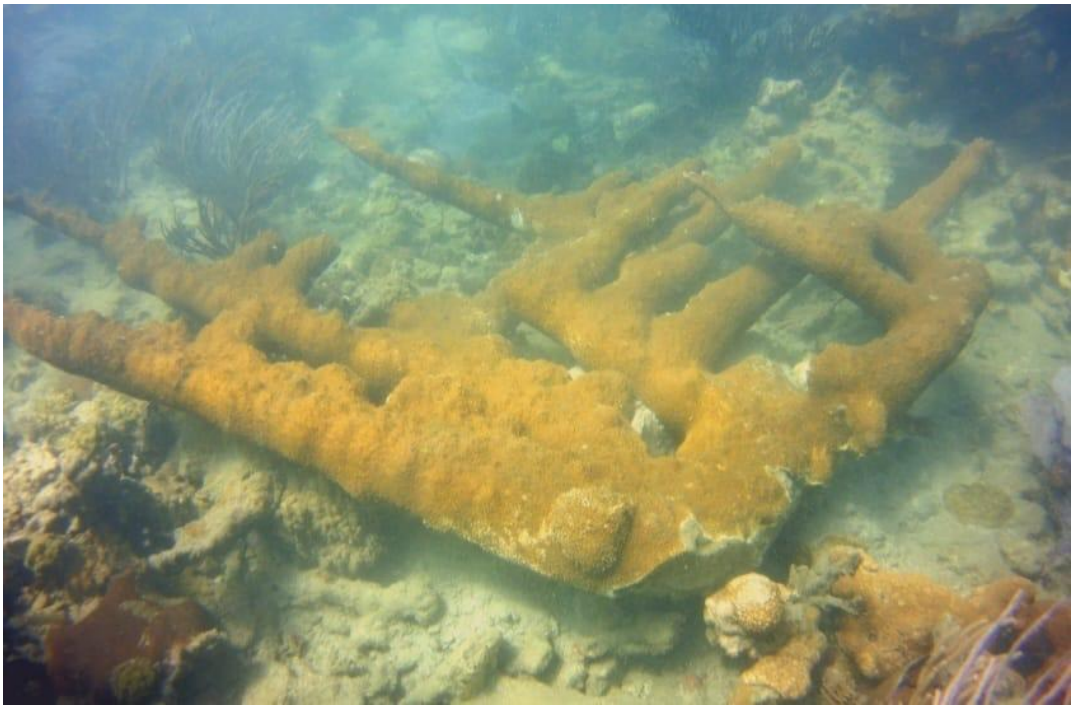


***Figure 7**. Large A. palmata colony (267 cm maximum diameter) attached at Cayo Laurel*

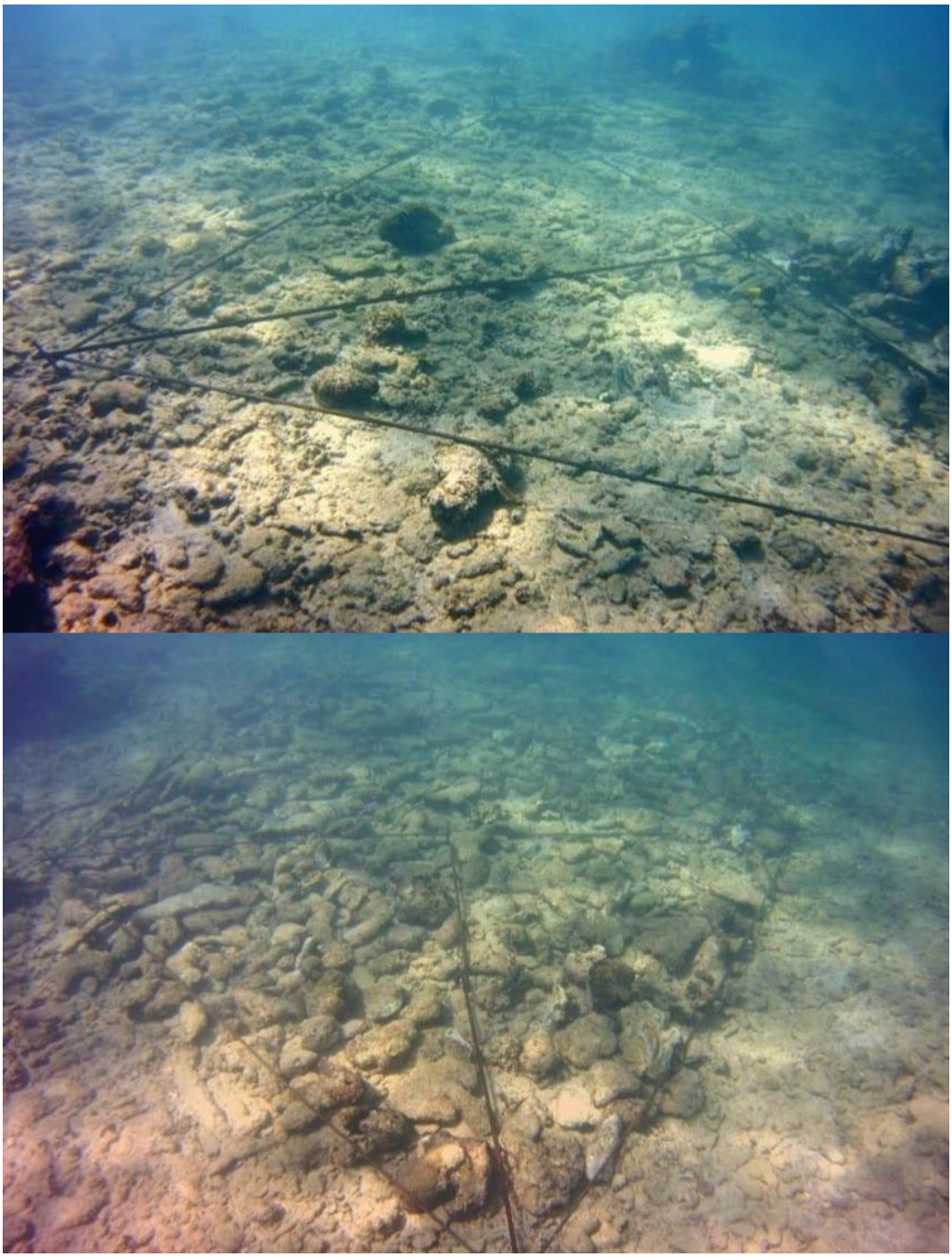


Figure 8. *Rubble stabilization setup. A framework of half inch rebar is installed in the benthos and filled with rubble pieces. Subsequently, cement is poured and spread to fix the rebar and maximize surface contact with the rubble. Once hardened, the cement and rebar trap rubble in place. Eventually, corals can be outplanted on the resulting structure.*

***Figure 9**. After Rubble stabilization setup with outplanted corals at HFO9, Cayo Coral.*

Photogrammetry analyses revealed that the size of outplants varied considerably between plots. For example, based on average planar area, at the forereef plot at Cayo Laurel (HFLO2) fragments measured 567 cm^2, while fragments at the backreef plot at Cayo Coral (HFO9) measured 173 cm^2 (Figure 10A). Despite large variability in size within each plot, differences among the plots was evident when compared to Cayo Laurel, where large colonies were overturned and stabilized using lift-bags. Less variability in outplants sizes, estimated as maximum linear distance, was documented by HJR Reefscaping at Rincon, El Negro and Cayo Aurora (Figure 10B).

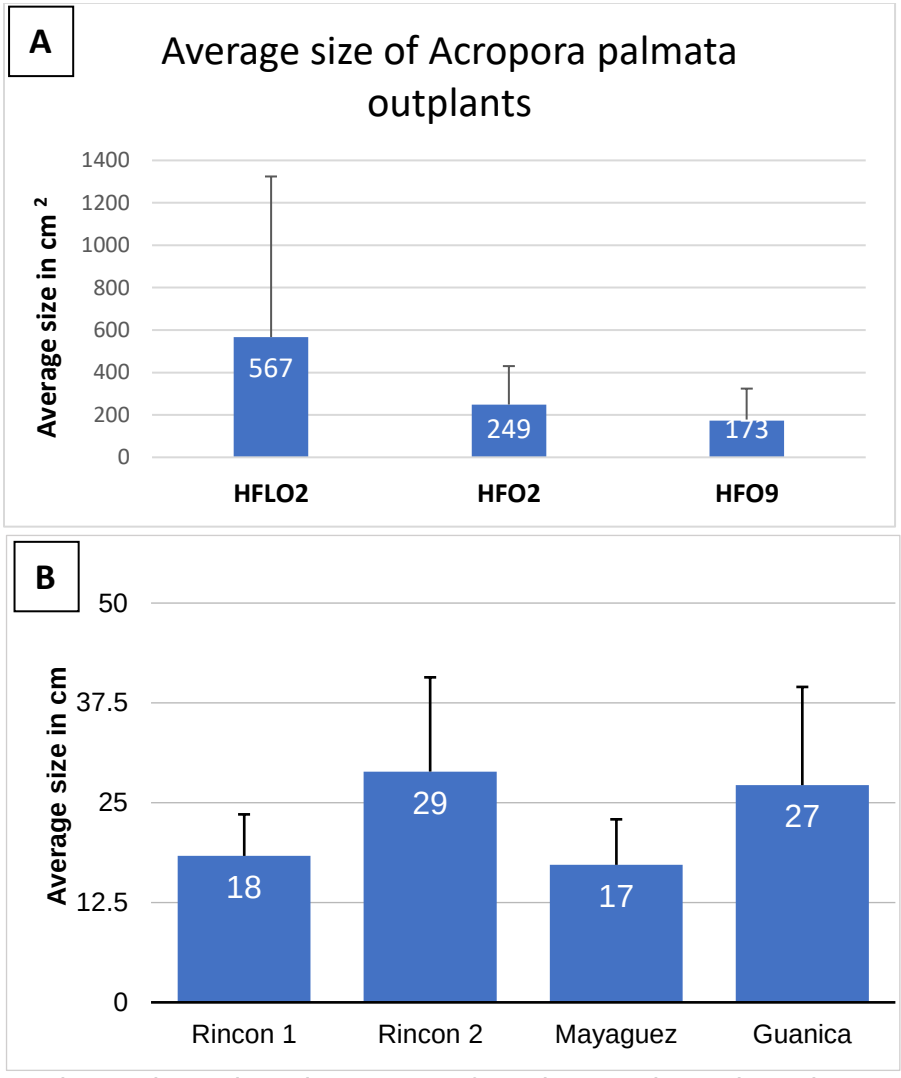


***Figure 10**. Average size, estimated as planar area, of outplants at three plots where orthomosaics were produced by Sea Ventures MRU and (B) Average size, estimated as linear distance, of outplants in sites by HJR Reefscaping.*

Photogrammetry analyses showed that, on average, outplanted *A. palmata* fragments covered 2.7 % of the benthic cover in three plots where orthomosaics were produced by Sea Ventures MRU, while Cliona covered 1.8 %, and Rubble covered 31 %. The cover % of outplanted fragments was consistent across plots (Figure 11). Cliona spp. cover was relatively low as expected based on the plot-selection criteria. The benthic category of interest with the greater variability was rubble, increasing dramatically in backreef areas, as evidenced by the plot in Cayo Coral Backreef (HFO9). This area was selected for outplanting given the completion of rubble stabilization, an intervention which provides clean additional stable substrate for the outplants to overgrow in areas of optimum growth but which are structurally compromised. In Cayo Coral, backreef areas seemed to provide key benefits to outplants such as good water circulation and relatively low breaking wave exposure compared to forereef areas, increasing the likelihood of fragment attachment in the short and long-term.

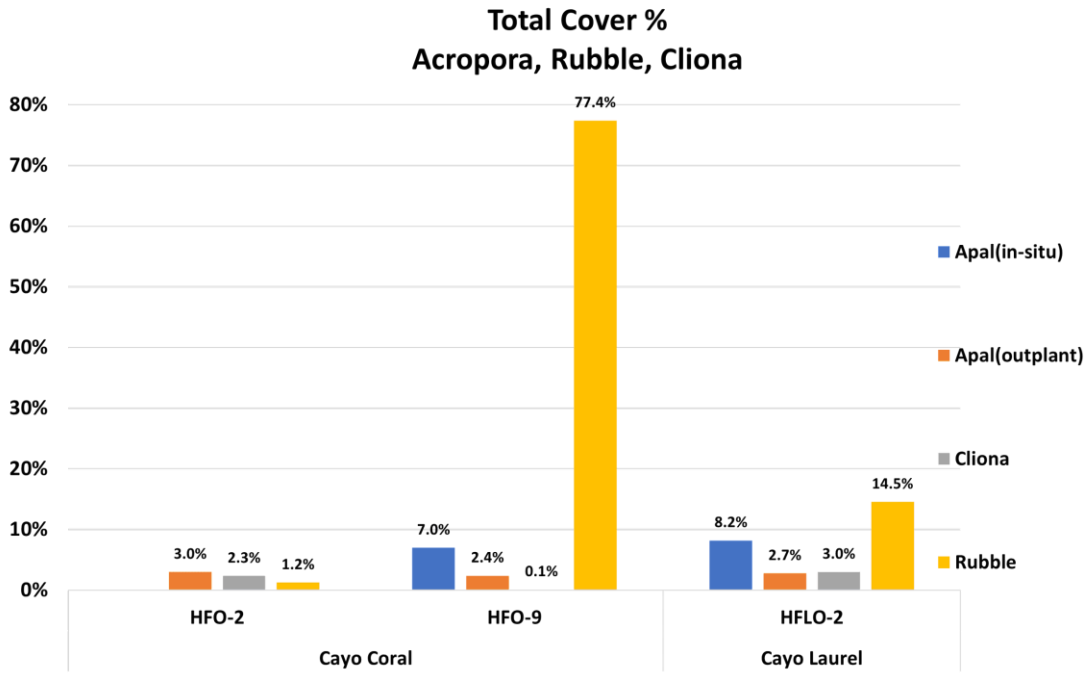


Figure 11*. Cover % of benthic categories of interest estimated from photogrammetry analysis in TagLab at three plots where orthomosaics where produced by Sea Ventures MRU.*

Cayo Coral Restoration Target Area

Since the impacts of Hurricane Matthew swells in 2016, Sea Ventures have sustained triage and subsequent propagation efforts to enhance *A. palmata* populations in both forereef and backreef habitats of Cayo Coral. This site has provided high survival rates and growth, and the unique opportunity to monitor and plan according to long-term restoration targets given sustained funding to respond to recurring storms. Currently, based on completed work, reef geomorphology, and habitat characteristics, the restoration target area at Cayo Coral has been estimated to be around 33,770 m2. This area includes a continuous forereef barrier from east to west and a second designated backreef barrier to capture fragments of opportunity during storms and perform rubble stabilization (Figure 12). After the Hurricane Fiona work, a total of 13,250 m2 within the target area (39%) have been impacted by restoration activities. Efforts done in response to Hurricane Matthew since 2016 contributed to a total area of 11, 606 m2 while Fiona efforts achieved a total area of 1,644 m2 since November 2022.

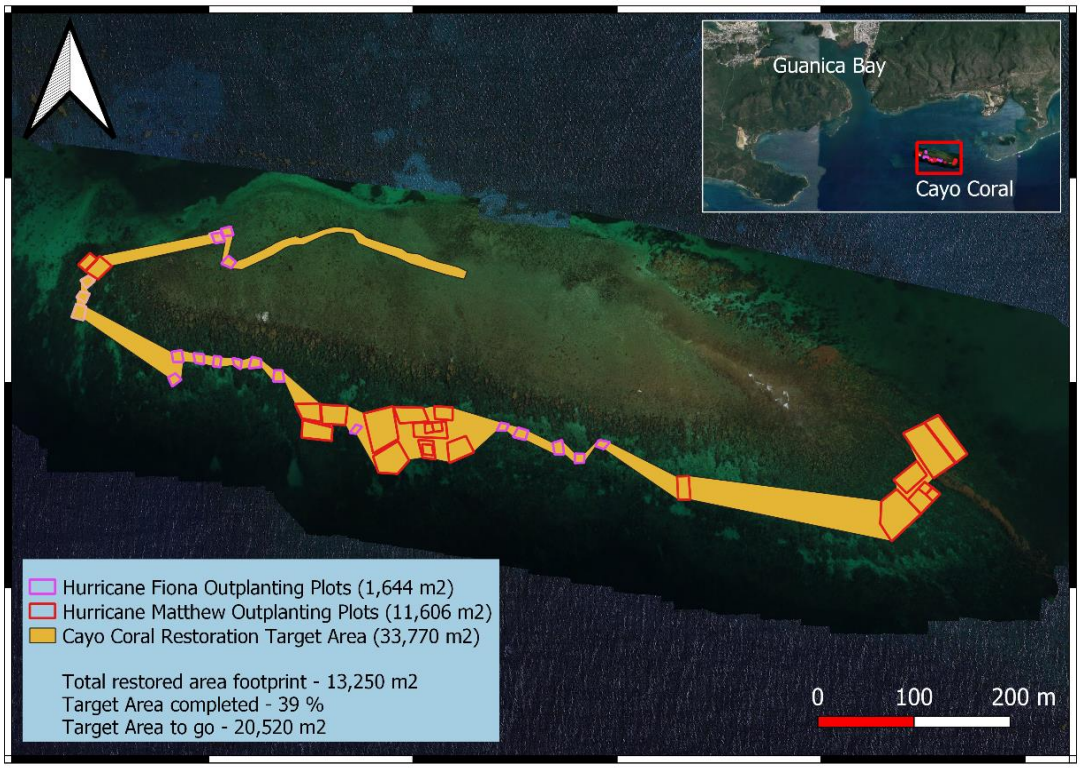


Figure 12. *Map of Cayo Coral Restoration Target Area and outplanting plots completed since emergency response efforts in 2016.*

Conclusions and recommendations

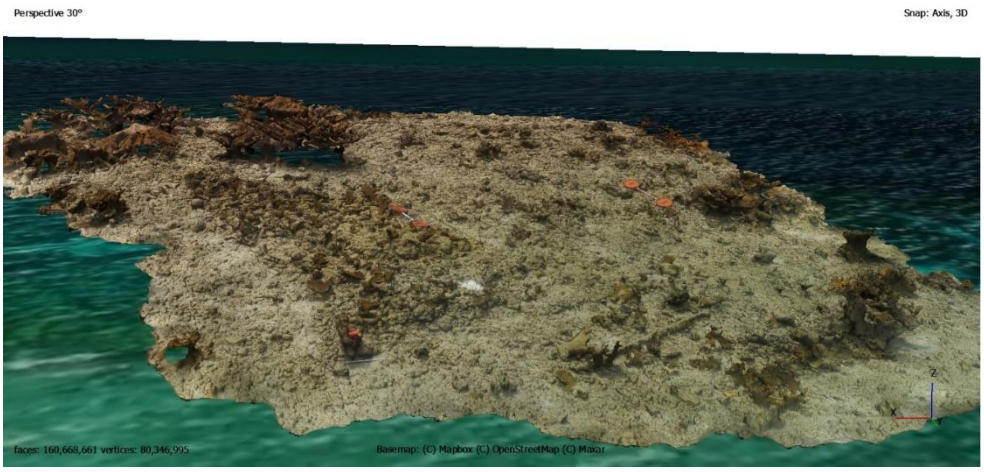
- A total of 6,000 *A. palmata* fragments and 96 colonies were triaged after Hurricane Fiona across multiple reefs supporting the much-needed survival of wild Acropora populations. This amount of outplanted corals as fragment of opportunities would take years to be produced from nursery programs.
- Permanent plots were established to characterize the triage efforts and expand the capacity of monitoring outplants survival and growth by the use of photogrammetry. It is recommended to support future monitoring of these plots which have been described in this report as baseline conditions.
- However, there are still thousands of *A. palmata* fragments from this event that are still loose (APPENDIX II) and at risk of dying creating another problem like loose rubble, and issue that has creates a constant threat to extant populations during high wave energy events.
- We have stabilized the old rubble in some areas creating a solid structure that will eliminate potential rubble projectiles, restore the mechanical damage on the reef with a solid substrate for the new fragments to be attached, and create new habitat.
- Respectfully we ask to be considered for additional funding opportunities to continue with coral restoration work and rubble stabilization since there are still a lot fragments detached from Fiona that will not attach well or attach to unstable substrate that do not provide long-term survival. This is key to the output of the implemented triage efforts.

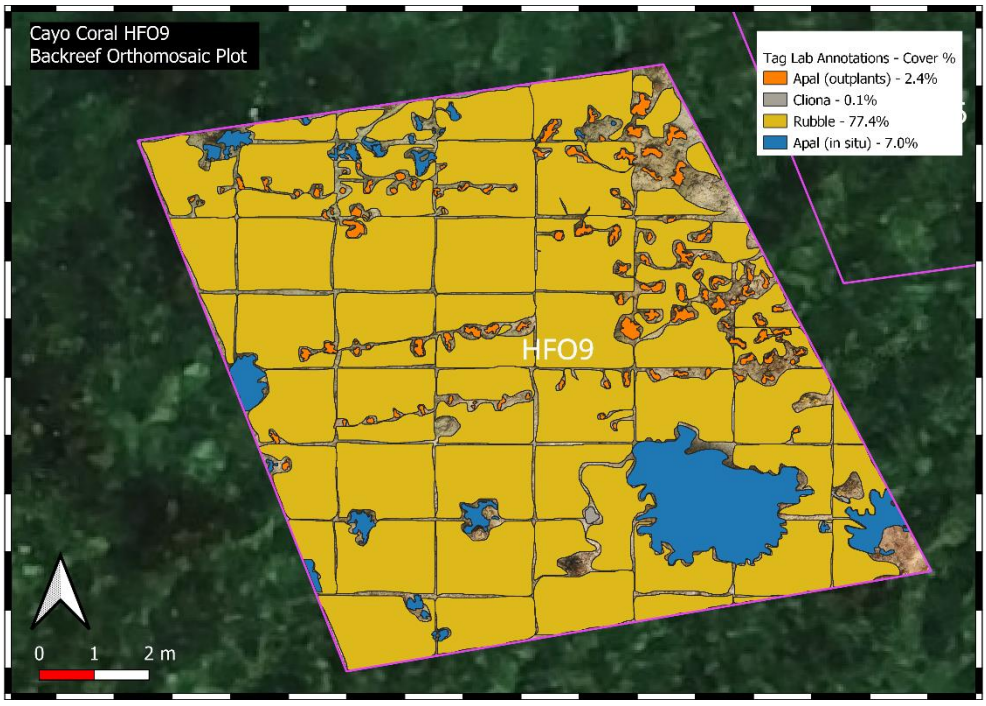
APPENDIX I. Orthomosaics and 3D models produced[1]

Site: Cayo Coral (Backreef)

Plot: HFO9

Credit: Sea Ventures MRU



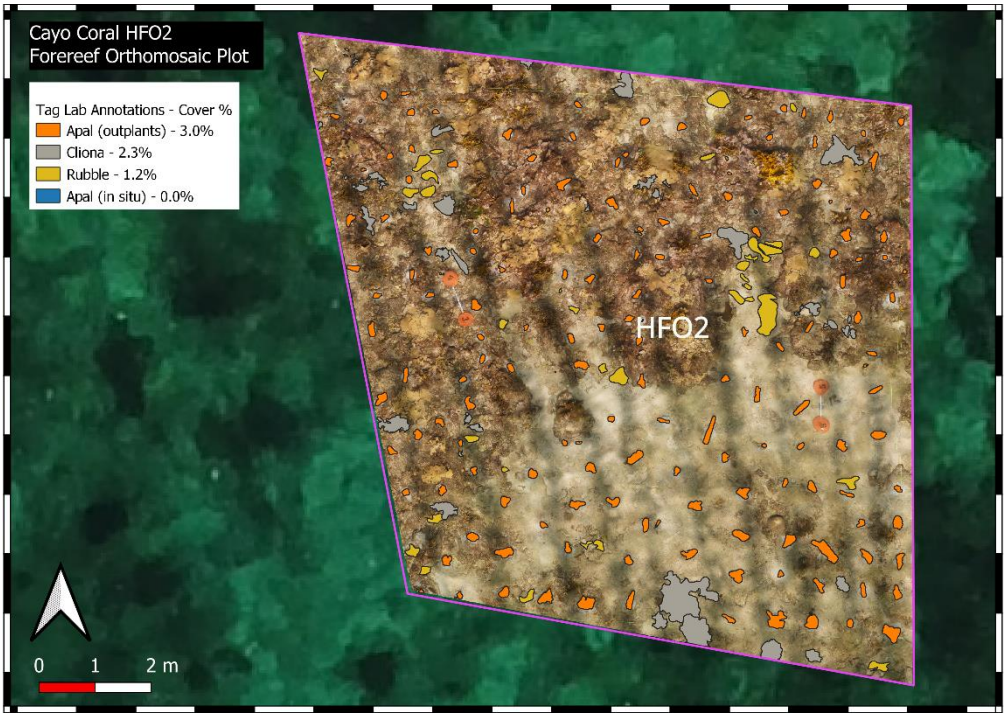


[1] 3D Model and georeferenced orthomosaic, and their TagLab annotation files are available upon request. Contact pedrocoralrestoration@gmail.com, mfiguerolahernandez@gmail.com, and astreoides@gmail.com for further information.

Site: Cayo Coral Forereef

Plot: HFO2

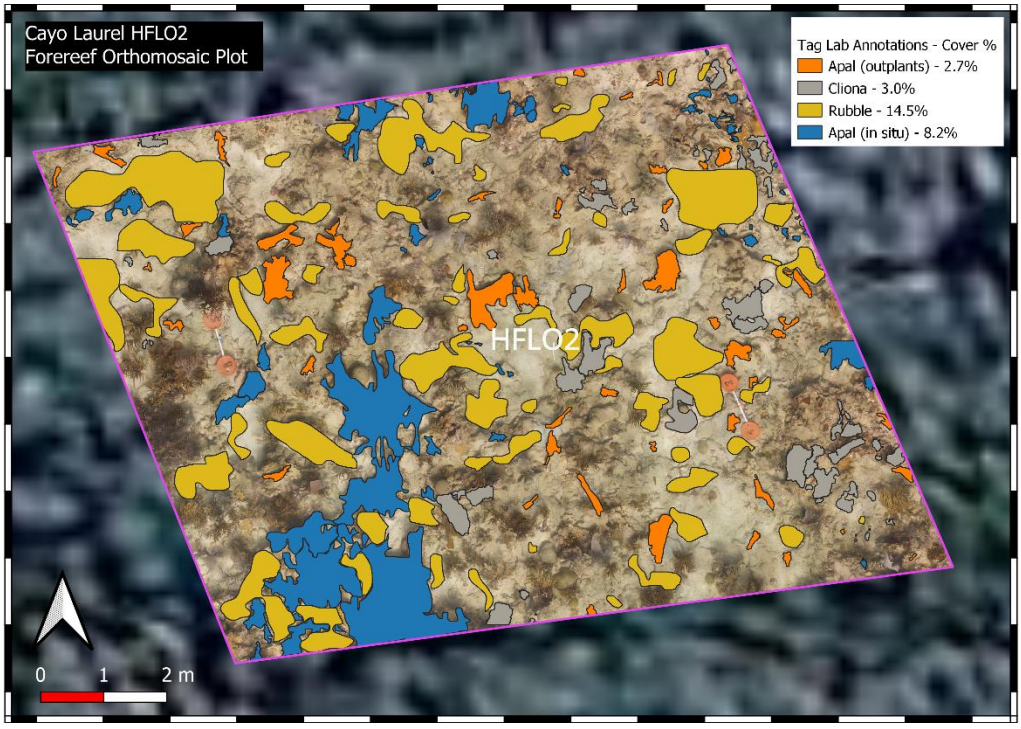
Credit: Sea Ventures MRU



Site: Cayo Laurel Forereef

Plot: HFLO2

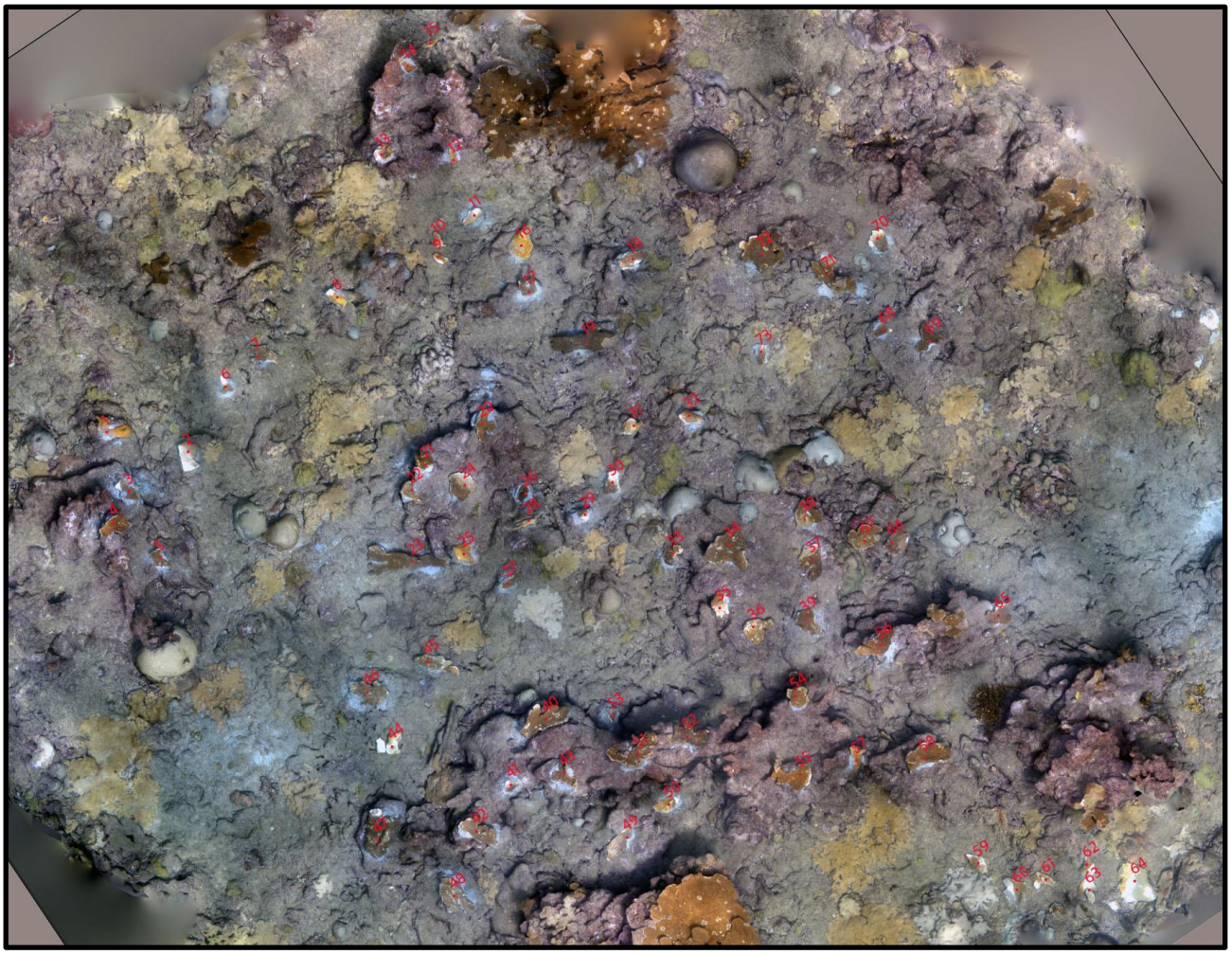
Credit: Sea Ventures MRU



Site: Rincon 1

Plot: Wp 251

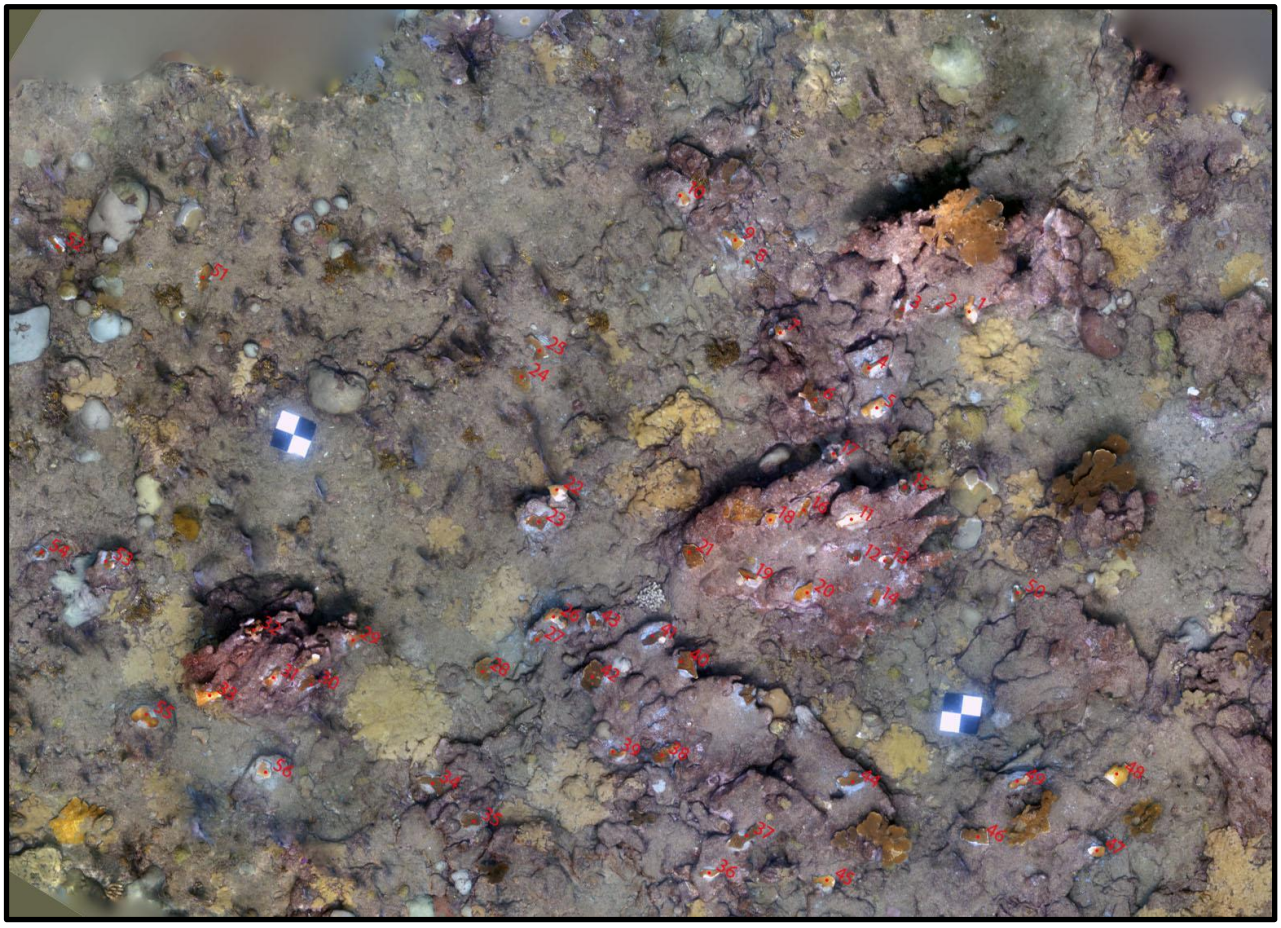
Credit: HJR Reefscaping



Site: Rincon 2

Plot: Wp 249

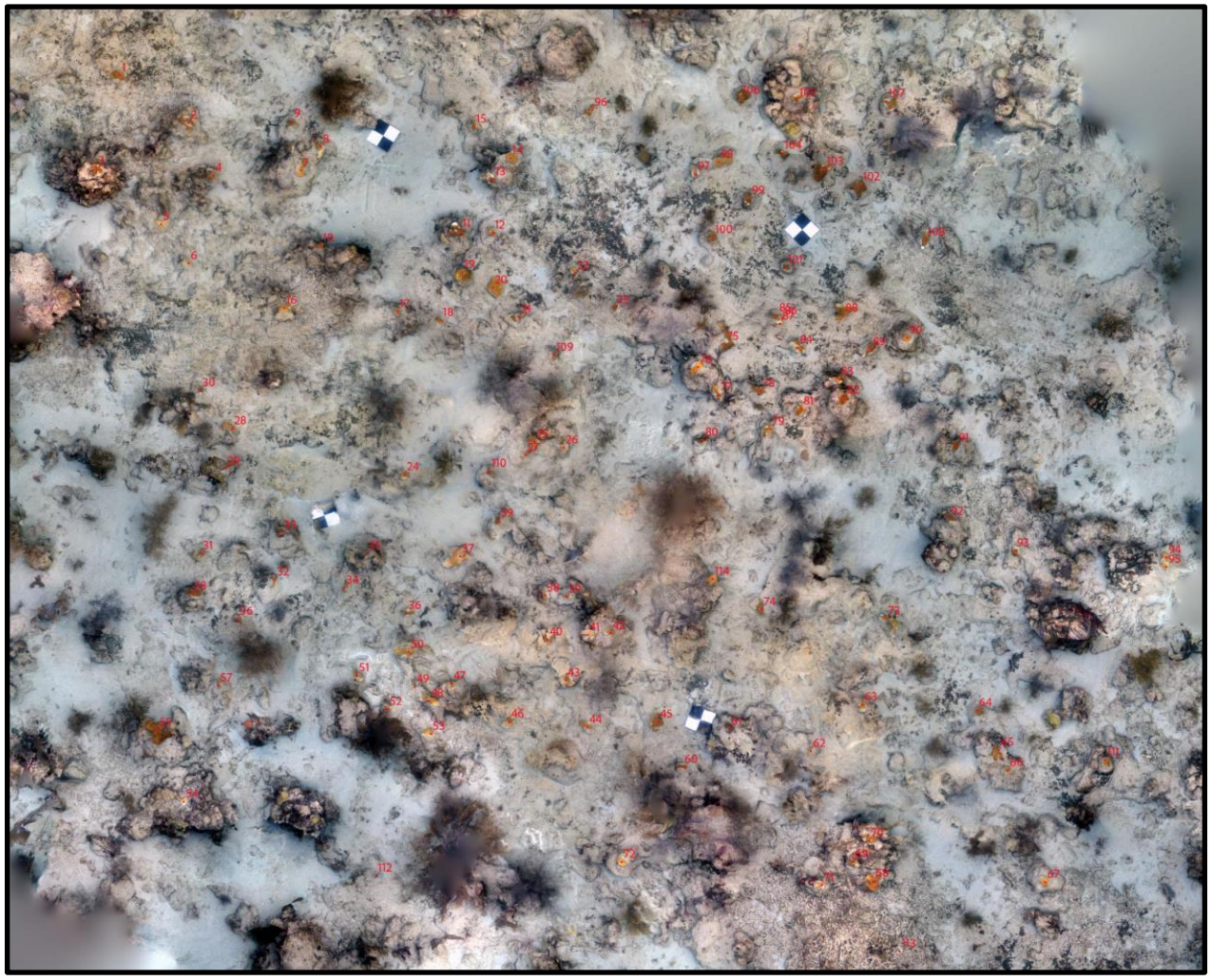
Credit: HJR Reefscaping



Site: El Negro

Plot: Wp 216

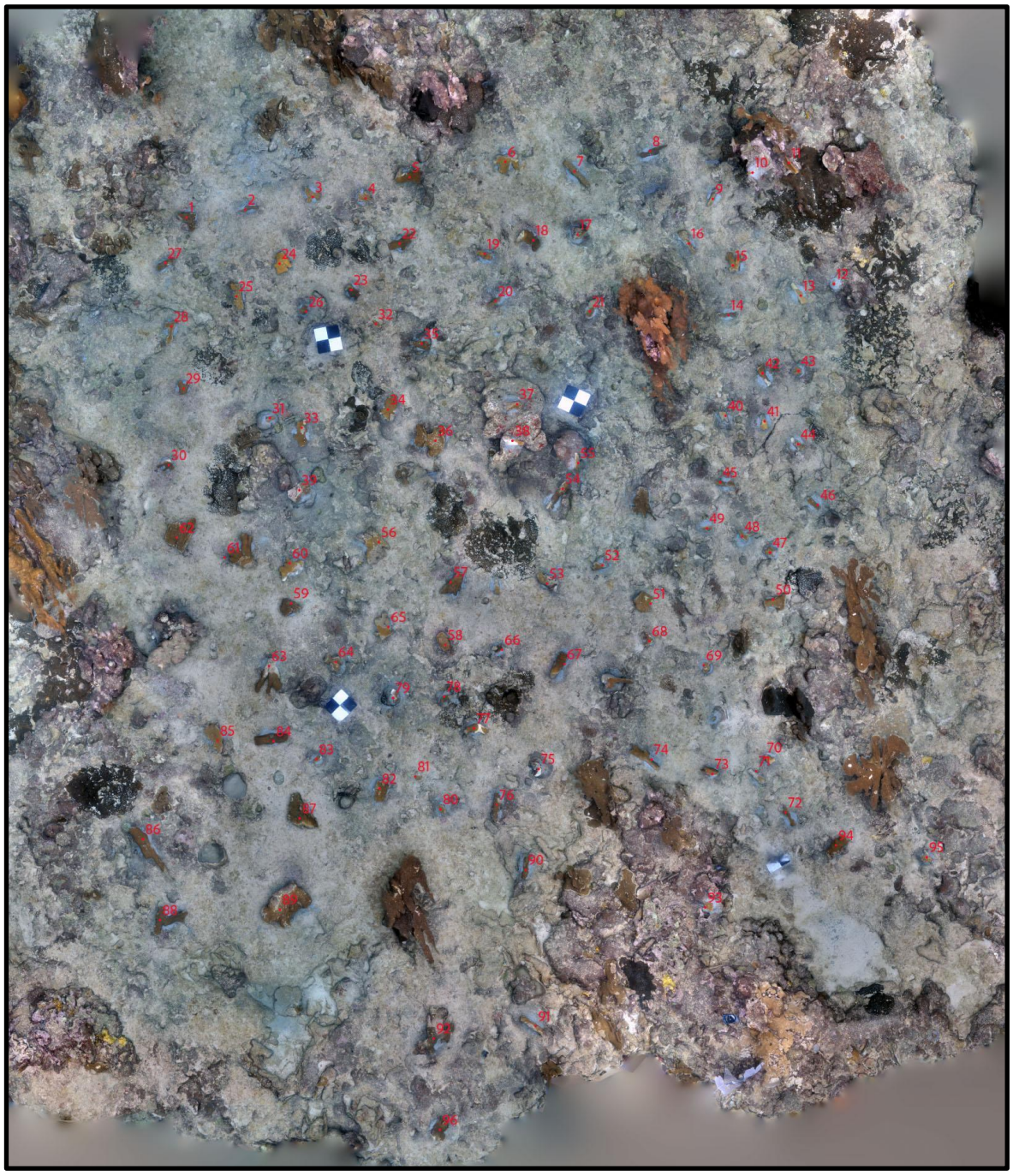
Credit: HJR Reefscaping



Site: Cayo Aurora

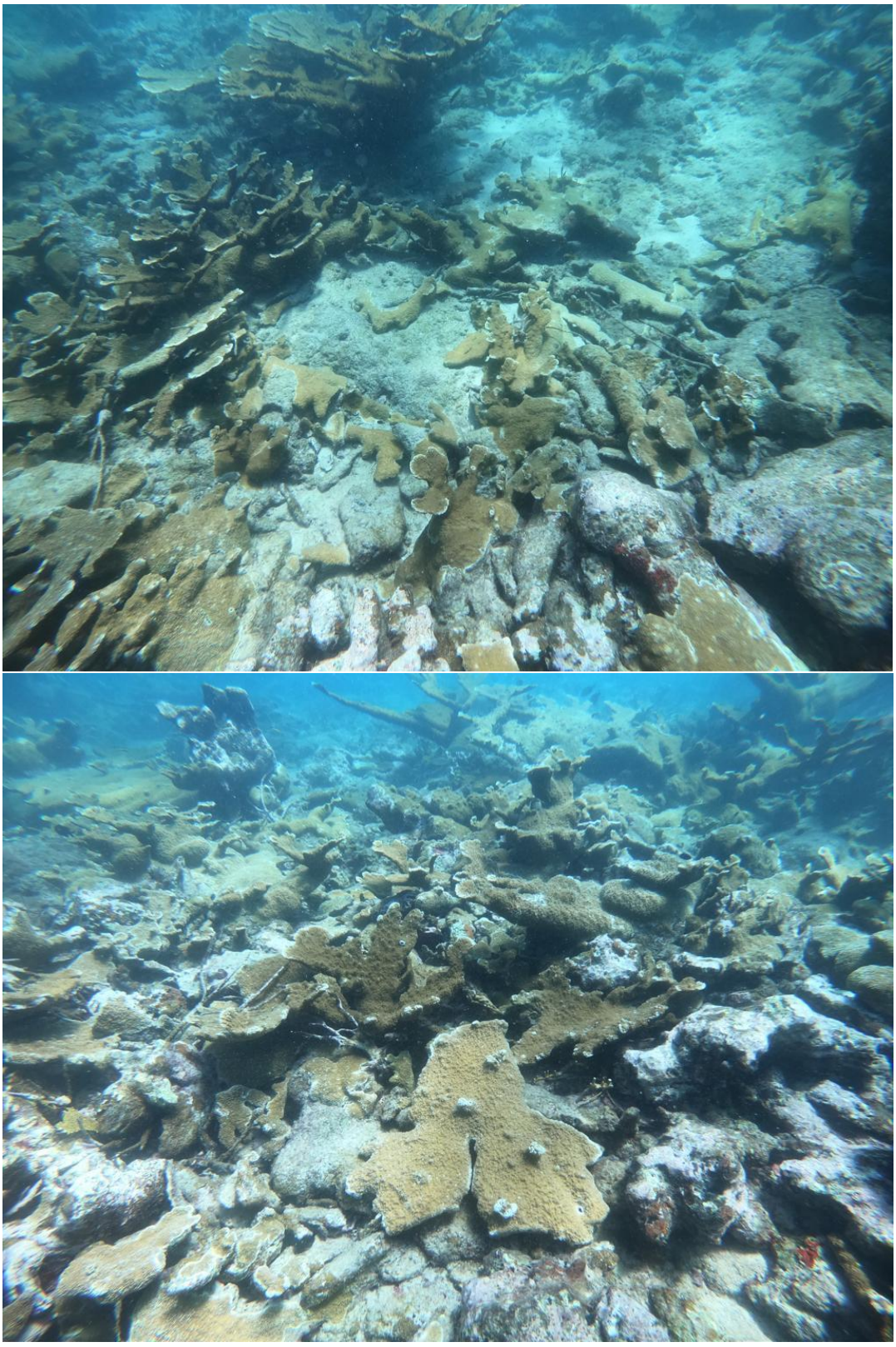
Plot: Wp 217

Credit: HJR Reefscaping



APPENDIX II. At-risk fragments that need further triage[2]

[2] Colonies at-risk documented on March 3 - 2023 in Cayo Aurora, Guanica.



[2] Colonies at-risk documented on March 3 - 2023 in Cayo Aurora, Guanica.