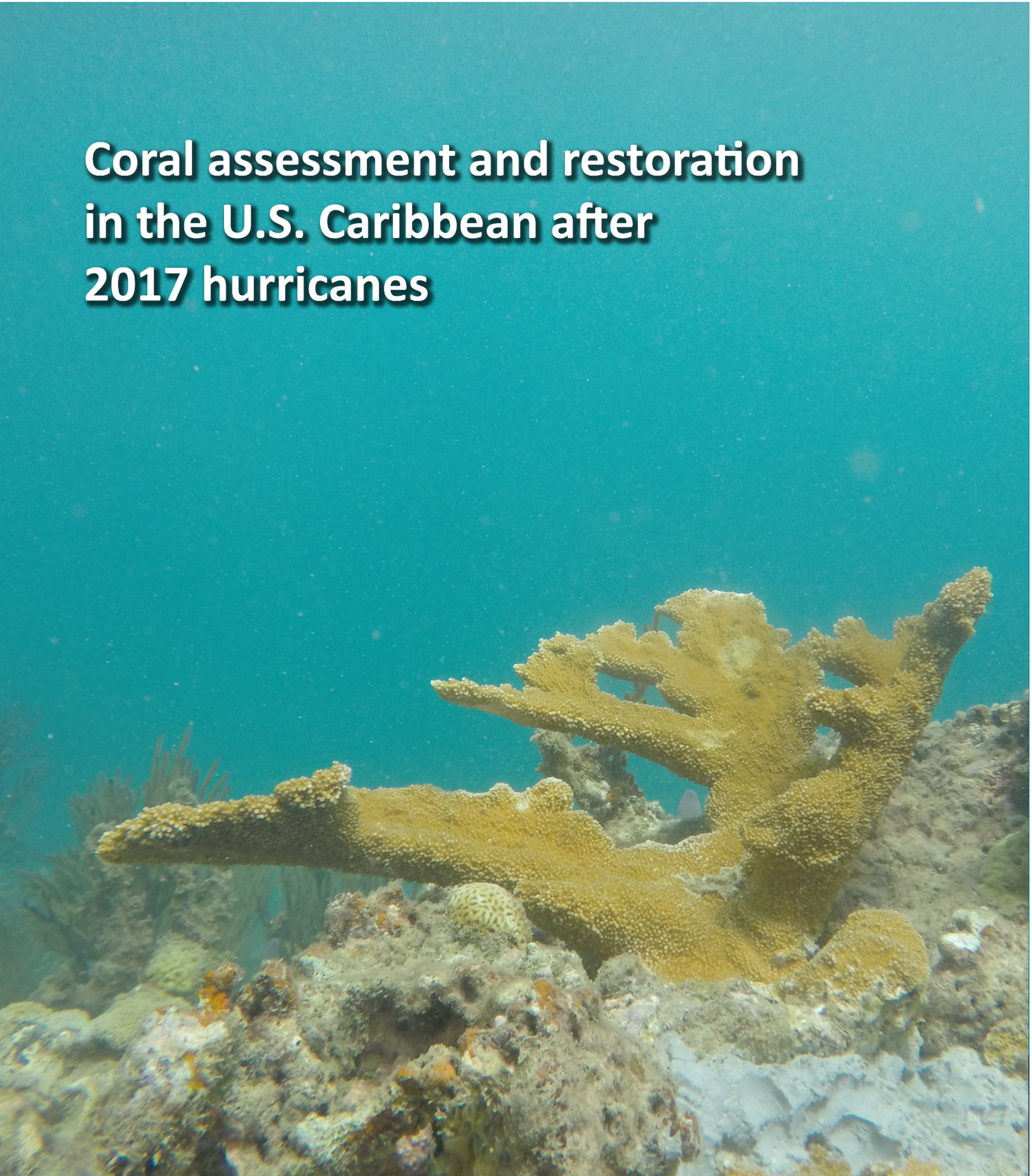
Coral assessment and restoration in the U.S. Caribbean after 2017 hurricanes



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Coral assessment and restoration in the U.S. Caribbean after 2017 hurricanes

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NOAA TECHNICAL MEMORANDUM NOS NCCOS 278

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ABOUT THIS DOCUMENT

The mission of the National Oceanic and Atmospheric Administration (NOAA) is for science, service, and stewardship, specifically to 1) understand and predict changes in climate, weather, oceans, and coasts; 2) share that knowledge and information with others; and 3) conserve and manage coastal and marine ecosystems and resources. The National Centers for Coastal Ocean Science (NCCOS) provides federal partners and coastal managers with the information and tools they need to balance society's environmental, social, and economic goals. NCCOS is the primary coastal science arm within NOAA's National Ocean Service (NOS). NCCOS works directly with managers, industry, regulators, and scientists to deliver relevant, timely, and accurate scientific information and tools.

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EXECUTIVE SUMMARY

In September 2017, major Hurricanes Irma and Maria impacted Puerto Rico and the U.S. Virgin Islands (USVI) and caused considerable damage to shallow coral reefs. In February 2018, at the request of the Puerto Rico Department of Natural and Environmental Resources (PRDNER), the Federal Emergency Management Agency (FEMA) assigned the National Oceanic and Atmospheric Administration (NOAA) to conduct coral reef assessments and emergency coral stabilization activities in Puerto Rico as part of the Hurricane Maria response under the National Disaster Recovery Framework Natural and Cultural Resources Recovery Support Function. A total of 414,354 m^2 of coral reef area, including over 87,000 corals, were assessed at 150 sites across Puerto Rico between February 27 and May 7, 2018. More than 8,700 corals were reattached at 35 reef sites in Puerto Rico. Prior to the FEMA effort, coral stabilization efforts were supported by NOAA and the National Fish and Wildlife Foundation (NFWF) in Puerto Rico and St. Thomas, USVI and reattached more than 7,500 corals at 28 additional sites. In total, coral stabilization efforts in PR and the USVI reattached 16,000 corals at 63 sites.

Hurricane damage of destabilized, broken, and loose corals was observed at approximately 12% of shallow reefs assessed in Puerto Rico. Damage varied between geographic regions, sites, and species. The most severely impacted coral species include four listed as Threatened under the Endangered Species Act (ESA): *Dendrogyra cylindrus* (pillar coral), *Acropora palmata* (elkhorn coral), *Orbicella annularis* (lobed star coral), and *Acropora cervicornis* (staghorn coral). Considerable variability was observed between assessment sites in the extent of wave impacts to corals and reefs, likely due to reef exposure to the dominant wave energy and coral species, abundance, size, and morphology.

Stabilization of loose or fragmented corals not only salvages the coral colony but also prevents future additional reef damage when the loose corals or rubble would be further mobilized in subsequent wave events (e.g., swells, tropical storms). Coral stabilization efforts reattached thousands of at-risk corals that would have otherwise perished. Many reattached corals were fragments from large, slow-growing species that are hundreds of years old. Saving these large individuals was intended to contribute to maintaining overall coral biomass, ecosystem functionality, reef potential for wave attenuation, and habitat quality for other coral reef organisms (e.g., fish, invertebrates), resulting in local and regional improvements to habitat and species abundance and diversity.

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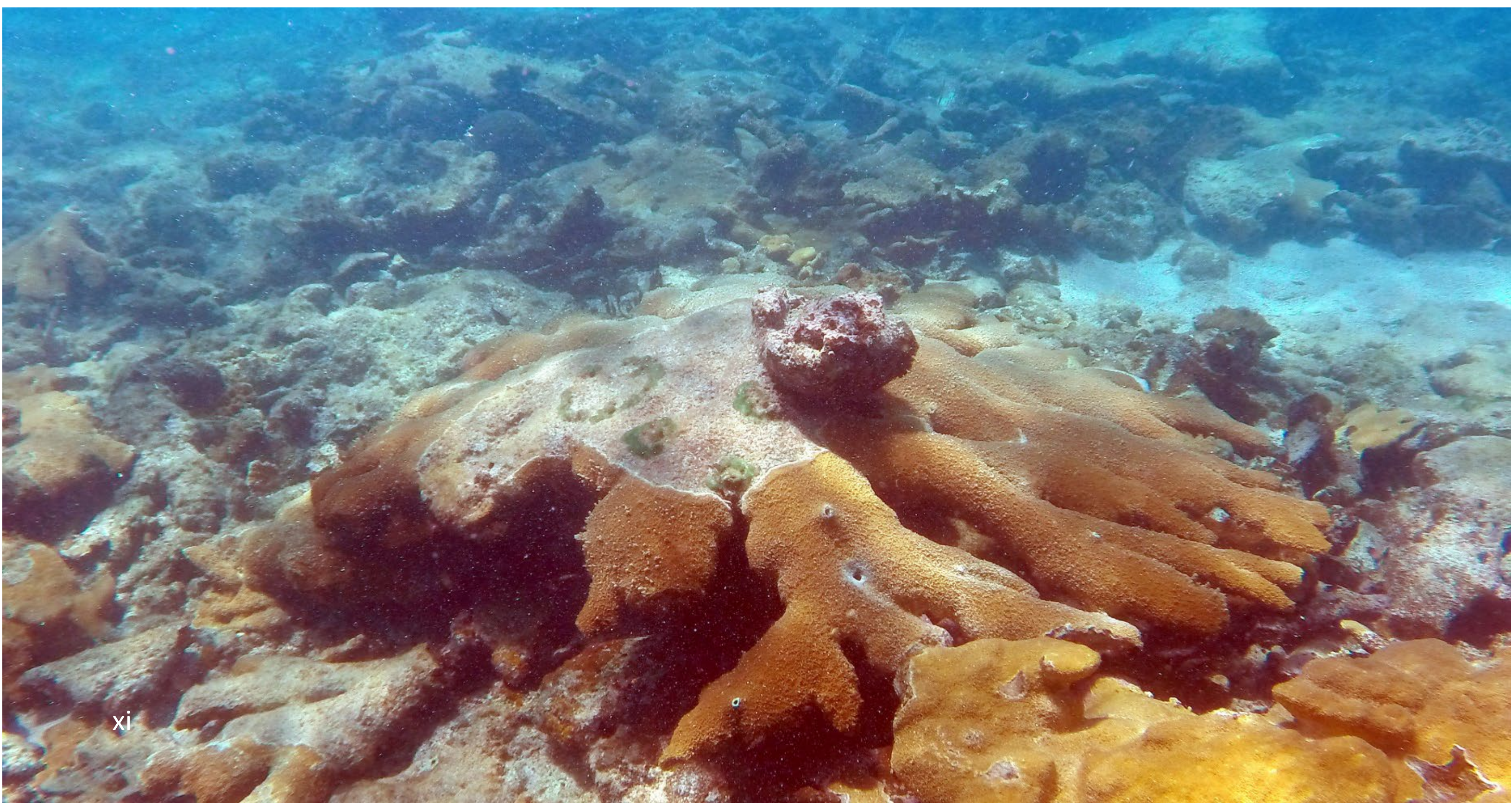
LIST OF ACRONYMS

Airbus DS	Airbus Defence and Space
CNES	Thales Alenia Space and French space agency Centre National d'Etudes Spatiales
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
FRC	Fundamental Research Communication
GOES	Geostationary Operational Environmental Satellite
GIS	Geographic Information Systems
GPS	Global Positioning System
IGN	Institut National De L'Information Geographique Et Forestiere
ISODATA	Iterative Self-Organizing Data Analysis Technique
N-S-E-W	North-South-East-West (cardinal directions)
NCCOS	National Centers for Coastal Ocean Science
NCRMP	National Coral Reef Monitoring Program
NFWF	National Fish and Wildlife Foundation
NGIA	National Geospatial Intelligence Agency
NHC	National Hurricane Center
NMFS	National Marine Fisheries Service (NOAA Fisheries)
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
PR	Puerto Rico
PRDNER	Puerto Rico Department of Natural and Environmental Resources
SfM	Structure from Motion photogrammetry
U.S.	United States
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USVI	United States Virgin Islands
UWCIMSS	University of Wisconsin-Madison Cooperative Institute of Meteorological Satellite Studies

SPECIES ABBREVIATIONS

ACR CERV	*Acropora cervicornis* (staghorn coral)
ACR PALM	*Acropora palmata* (elkhorn coral)
ACR PROL	*Acropora prolifera* (fused staghorn coral)
BR POR SPP	Branching *Porites* species (finger coral)
COL NATA	*Colpophyllia natans* (boulder brain coral)
DEN CYLI	*Dendrogyra cylindrus* (pillar coral)
DIP LABY	*Diploria labyrinthiformis* (grooved brain coral)
MON CAVE	*Montastrea cavernosa* (great star coral)
ORB ANNU	*Orbicella annularis* (lobed star coral)
ORB FAVE	*Orbicella faveolata* (mountainous star coral)
ORB FRAN	*Orbicella franksi* (boulder star coral)
POR ASTE	*Porites astreoides* (mustard hill coral)
PSE CLIV	*Pseudodiploria clivosa* (knobby brain coral)
PSE STRI	*Pseudodiploria strigosa* (symmetrical brain coral)
SID SIDE	*Siderastrea siderea* (massive starlet coral)



INTRODUCTION

Coral reefs buffer coastlines from erosion and inundation and reduce risk to people and infrastructure from wave damage and flooding (Spalding et al. 2014). Globally, coral reefs reduce wave energy by 97% and reduce wave height by 84% (Ferrario et al. 2014). In Puerto Rico and the U.S. Virgin Islands (USVI), specifically, coral reefs provide coastal protection for more than 4,500 people and are estimated to provide more than $230,000,000 annually in protection benefits (Storlazzi et al. 2019). Hurricanes and extreme wave energy affect coral reefs worldwide (e.g., Stoddart 1962; Harmelin-Vivien 1994); however, as reefs continue to decline, particularly in the Caribbean, the potential for reefs to provide effective coastal protection may be reduced due to the loss of reef structural complexity and the key coral species that create reef structure (Alvarez-Filip et al. 2009).

In September 2017, Hurricanes Irma and Maria caused widespread catastrophic wind and flood damage to Puerto Rico and the U.S. Virgin Islands. Hurricane Irma made landfall in the British Virgin Islands, just east of the U.S. Virgin Islands, on Sep. 6, 2017 as a 155 kt category 5 hurricane (Cangialosi et al. 2018). Significant coastal inundation likely occurred on St. Thomas and St. John in the U.S. Virgin Islands, although specific estimates are not available (Cangialosi et al. 2018). Maximum inundation in Puerto Rico from Hurricane Irma was estimated at 1-2 ft. Hurricane Maria made landfall on Sep. 20, 2017 in southeastern Puerto Rico as a high-end category 4 hurricane with a landfall intensity of 135 kts (Figure **1**). Hurricane Maria was the

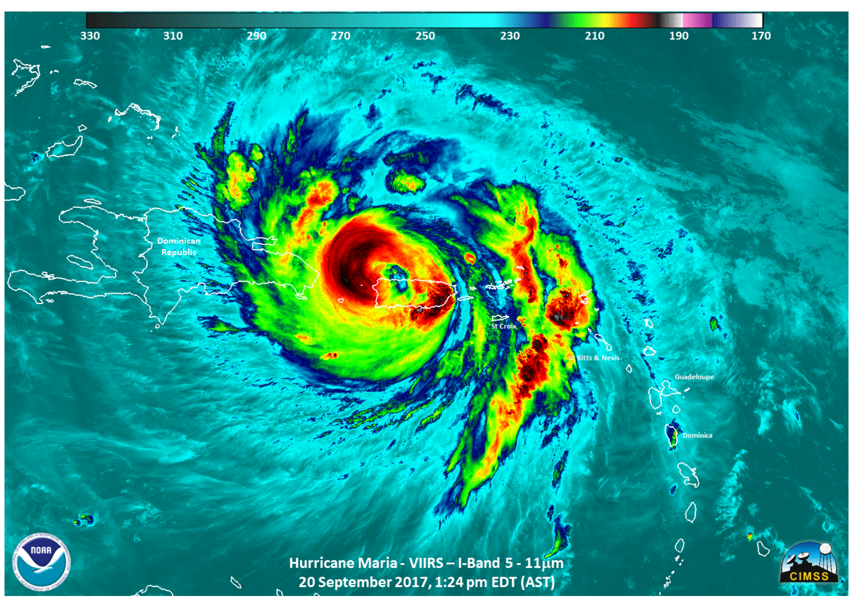


Figure 1. Hurricane Maria exiting Puerto Rico (Pasch et al. 2017).
Image credit: NOAA NHC and UW CIMSS.

strongest hurricane to make landfall in Puerto Rico since 1928. The southeast region of Puerto Rico showed maximum coastal inundation levels from 6-9 ft. Coastal inundation was estimated at 3-5 feet occurred on the east coast of Puerto Rico, and the south coasts of Puerto Rico, Vieques, and St. Croix, and 2-4 feet on the north coast of Puerto Rico, including San Juan (Pasch et al. 2019). The damage in Puerto Rico and the U.S. Virgin Islands from Hurricane Maria is estimated at $65-115 billion dollars, the third costliest hurricane to date (Pasch et al. 2019).

In addition to the significant damage that the 2017 hurricanes inflicted on terrestrial infrastructure and resources in the U.S. Caribbean, storm-related wave energy caused damage to coral reefs. In-water observations in Puerto Rico and the USVI soon after the 2017 hurricanes indicated that damage to corals and coral reefs appeared extensive. Observed damage included overturned large coral heads, extensive coral colony breakage, coral colony burial by sediment, and large areas of loose rubble. In particular, dense thickets of *Acropora palmata* (elkhorn coral) and patch reefs of *Orbicella annularis* (lobed star coral) showed significant colony breakage from the hurricanes. Both of these species are primary reef-builders in shallow depths, and as such are key species for creating and maintaining reef complexity for coastal protection (Figure 2). Furthermore, these species are listed as Threatened under the Endangered Species Act (ESA; NMFS 2006, 2014).

Corals that have been physically impacted have a significantly greater chance of survival when reattached to the substrate than those left loose (Meadows & Bosnan 2008; McLeod et al. 2019). Broken, loose, or fragmented corals can remain alive on the seafloor but are at high risk of mortality from being tumbled by subsequent storm waves or buried by sediment.

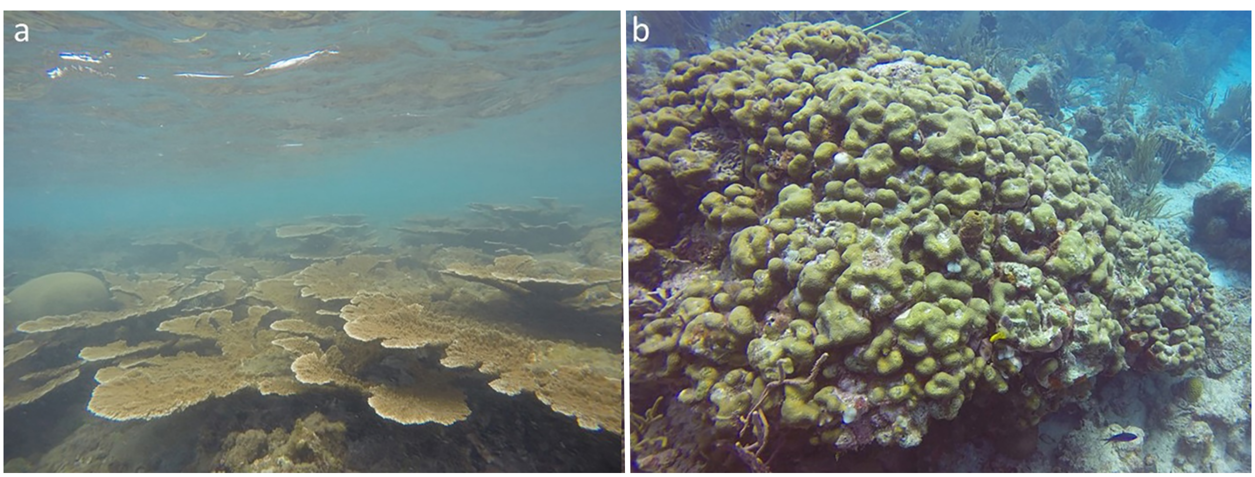


Figure 2. Undamaged coral species on shallow Caribbean reefs. *(a)* Thicket of *Acropora palmata* (elkhorn coral) and *(b)* patch of *Orbicella annularis* (lobed star coral). These coral species create three-dimensional, structurally-complex reefs that reduce wave energy and provide habitat for many coral reef organisms.

Reattaching loose corals to the reef substratum can lessen overall damage to reefs from wave energy and contribute to maintaining or restoring the functionality and services provided by reefs.

In Puerto Rico and the USVI, an initial emergency coral restoration effort was started in October 2017 to reattach at-risk corals. Puerto Rico Department of Natural and Environmental Resources (PRDNER) considered the preliminary estimates of damage to the natural infrastructure of coral reefs and identified the need for a large scale effort to assess coral reef damage from the hurricanes and to stabilize loose corals. PRDNER requested a natural and cultural resource damage assessment from the U.S. Federal Emergency Management Agency (FEMA), which resulted in a FEMA mission assignment to the National Oceanic and Atmospheric Administration (NOAA). The mission assignment in Puerto Rico consisted of: 1) an archipelago-wide assessment of the impacts of the hurricanes on coral reefs, and 2) emergency salvage efforts to stabilize and reattach live corals that were still viable. Impact assessments were used to identify highly impacted reefs and inform efforts to stabilize loose corals. This report summarizes both the pre-FEMA restoration effort in Puerto Rico and the USVI as well as the FEMA mission assignment in Puerto Rico.

In a complementary effort, reefs north of San Juan, Puerto Rico were mapped to provide information as part of planning for potential future large-scale, long-term coral restoration efforts to increase protection for coastal infrastructure in Puerto Rico. This area was identified as a priority restoration site based on a combination of damage assessment (from 2017 wave events), local knowledge of current and historical reef conditions, local management input, and proximity to coastal infrastructure and human population density. Remote sensing data and existing habitat maps were used to refine potential restoration areas by delineating hardbottom habitats within selected depth ranges on these reefs.

Objectives

1. Assess impacts to corals on coral reefs in Puerto Rico after Hurricanes Irma and Maria.
2. Identify sites for emergency coral stabilization in Puerto Rico.
3. Conduct emergency stabilization of loose and damaged corals in Puerto Rico and the USVI.
4. Map hardbottom habitat north of San Juan, Puerto Rico to support potential planning for future large-scale coral restoration.

METHODS

1. Coral Assessment

1.1. Survey Design

Coral reef and hardbottom habitats cover an estimated 756 km^2 of the seafloor around the archipelago of Puerto Rico (Kendall et al. 2001). Due to the extensive geographic area of coral reefs around Puerto Rico and the short duration of the mission, the coral reef assessment was a representative sampling effort. Survey sites were selected using a probabilistic, stratified weighted sampling design. The sample frame was adapted from NOAA's National Coral Reef Monitoring Program (NCRMP) survey effort (https://www.coris.noaa.gov/monitoring/). NCRMP biological sampling includes monitoring for reef coral demographics, benthic cover, and fish communities. In the U.S. Atlantic jurisdictions, NCRMP sampling began in 2013 and is implemented on an approximately biennial basis in each jurisdiction, including Puerto Rico, USVI, the Florida reef tract, and Flower Garden Banks National Marine Sanctuary. In Puerto Rico, NCRMP monitoring occurred in 2014, 2016, and 2019. The NCRMP sample frame consists of a sampling grid (50 m by 50 m cells) that encompasses all known shallow water coral reef habitat surrounding mainland Puerto Rico, Vieques, Culebra, and the islands within the NE Reserve corridor as identified from the most current NOAA benthic habitat maps for the geography, here, the Northeast Puerto Rico and Culebra Island - Benthic Habitat Map (Kågesten et al. 2015) and Benthic Habitat Map of Puerto Rico (Kendall et al. 2001). The eastern half of Vieques is not included in the NCRMP sample frame due to the presence of unexploded ordnance.

For the coral reef hurricane assessment effort, the NCRMP sample frame was truncated to coral-dominated reef habitats in depths less than 7 m based on preliminary reports from ad hoc surveys of the distribution of coral breakage in relation to reef depth. The preliminary observations on post hurricane coral reef damage by NOAA Restoration Center and local coral scientists indicated storm damage was most evident on reefs shallower than 7 m, although deeper depths had minor damage. A focus on depth shallower than 7 m maximized meeting the assessment goals. The geographic representation for the Puerto Rico archipelago was based on the sample frame stratified by the hurricane path (Figure 3, Table 1) and geographic region, as well as the coral reef habitat area based on classification from habitat maps. Sample effort was allocated proportionally to ensure approximately equal field effort between sites shallower than 3.5 m depth and sites that were 3.5 – 7.0 m depth based on the NCRMP sample frame and depths derived from LiDAR bathymetry. A total of 150 primary sites were allocated into strata (Table 1). Additional sites per region were identified to serve as alternative sites for primary sites that could not be assessed or where the absence of coral reef habitat was verified by divers.

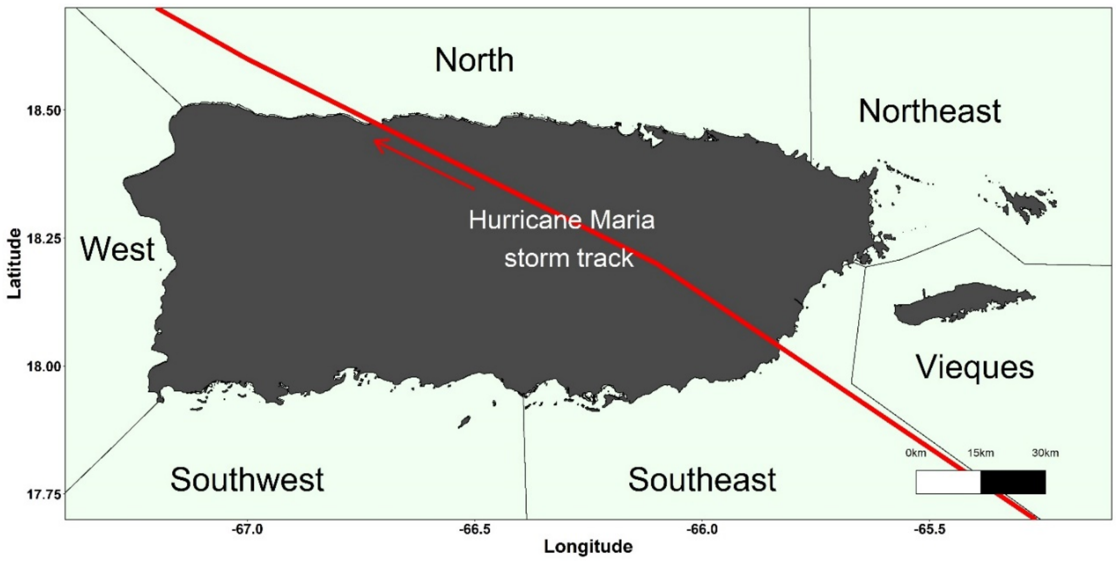


Figure 3. Geographic regions used in the assessment.The track of the eye of Hurricane Maria is shown in red, and the storm progressed from the southeast to the northwest. Hurricane Irma passed approximately 96 km (60 miles) north of Puerto Rico and is not shown.

Table 1. Number of planned sites per geographic region.

Region	Subregion	Number of planned sites
North	-	20
West	-	15
Southwest	-	15
Southeast	-	20
Northeast	NE /East PR Culebra	30 30
Vieques	-	20
TOTAL	-	150

1.2. Field Surveys

Coral assessment surveys included two types of in-water surveys conducted by divers. The objective of transect assessment surveys was to provide an assessment within a statistically valid sample frame to allow extrapolation to reef areas not surveyed. The objective of the roving surveys was to provide additional information on coral damage to prioritize site selection for coral stabilization efforts.

Transect assessment surveys were based on a stratified random sample design using the sample frame described in the previous section to allow for statistical extrapolation to provide regional estimates. These assessment surveys were conducted at site coordinates selected according to the sample design and independent of the presence of hurricane damage. Sites with less than 10% colonized hardbottom habitat were excluded from surveys. Each assessment diver conducted a 50 m long by approximately 5 m wide belt transect that bisected the survey grid cell (Figure 4; Appendix A), mindful of the direction of current and bathymetry, and minimizing diver separation for safety. Transect length and width were recorded (m) by each diver. Transect area truncation (shorten or narrow), or broadening (widen) was allowed as necessary due to field conditions (e.g., water visibility, wave energy, high damage, high coral cover) or benthic habitat (e.g., sand patches within reef). All transect area changes were recorded on the datasheet and incorporated into analyses (Table 2). At the center of the assessment survey area, divers took outward-facing photos in each cardinal direction (N-S-E-W) to capture a landscape representation of the site. Additional photos were also taken at each site to document the reef or impacts. In addition, benthic photographs were collected to illustrate examples of damaged and undamaged *A. palmata* reefs. These photographs were collected over an approximately 10 m x 10 m area, and photomosaics were assembled using Structure from Motion (SfM) photogrammetry.

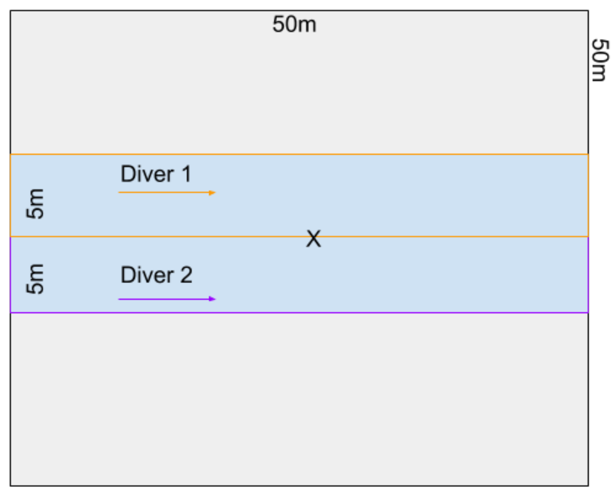


Figure 4. Representation of 2 diver transect survey areas (5 m x 50 m each) within a sampling grid cell (50 m x 50 m). 'X' marks the survey centroid GPS coordinates and target location for diver descent onto the survey site.

In addition to the transect assessment surveys, roving surveys were conducted to identify sites that would benefit from immediate coral stabilization and/or future restoration efforts (Appendix B). In the roving survey, divers could specifically target coral reef areas outside of the assessment transect that may have had impacts. In addition to roving surveys that occurred near the assessment area, roving surveys were conducted at nonrandom locations informed by local expert knowledge of high coral cover of reef-building coral species or expected damage. The survey area of the two roving divers was spatially variable based on reef characteristics and coral damage. Roving surveyors towed a GPS to record the trackline, recorded survey start and end times, and identified the width of their survey on their datasheets. The GPS trackline length was used in conjunction with survey width and survey start and end times to calculate the survey area. Areas where notes were collected were marked by time or by GPS point.

The following categorical evaluations were made during every transect assessment and roving survey: damage to site, damage to corals and/or framework, site potential for coral stabilization, and long-term restoration site potential (Table 2; Appendices A, B). To inform the potential need for coral re-attachment at a given site, assessment surveyors estimated the number of unattached corals within the 50 m x 50 m site, and roving surveyors estimated the number of loose corals within a specified survey area (Table 2). An estimate of rubble area at the site was also recorded.

Miguel Figuerola

Table 2. Classifications used to characterize assessment survey sites.The assessment survey datasheets are included in Appendices A and B.

Site description	Data type(s)
Survey depth (ft)	- Mean depth of surveyed area
Transect heading	- Direction of transect orientation
Visibility	- Visibility of water (m)
Hardbottom habitat	- Estimate of % in transect area - Estimate of % in 50 m x 50 m site * requirement of > 10% colonized hardbottom habitat for survey
Dominant habitat type	- Dominant reef habitat type [aggregate reef, patch, pavement, or bedrock] - Estimate (%) within transect area - Estimate (%) within 50 m x 50 m site
Rubble (%)	- Estimate of area of rubble as percent (%) of benthos
Estimated # of loose corals	- Estimate in 50 m x 50 m site - Estimate in surrounding area (estimate of area in m^2)
Level of damage to site	- None - Minor = < 10% damage to corals and reef - Moderate = 10 - 50% damage to corals and reef - Severe = > 50% damage to corals and reef
Damage to	- Corals - Framework - Both
Recommendation for coral stabilization	- High = > 300 corals to be reattached (> 20 cm) = many Threatened coral species impacted - Medium = > 100 corals to be reattached (> 20 cm) = some Threatened coral species impacted - Low = < 100 corals to be reattached - No damage
Recommendation for inclusion as a long-term restoration site	- High = Significant damage, restoration required for recovery - Medium = Moderate damage, might require restoration for recovery - Low = Damage present but natural recovery likely - No damage
Survey width (m)	- Width of assessment survey
Survey length (m)	- Total length of assessment survey
Photo documentation	- Photos, video, or none taken in survey

Surveys included all scleractinian species. All corals and fragments greater than 20 cm in skeletal size (in any dimension) or with at least 20 cm of living coral tissue were recorded in the survey. All observed corals were recorded by species and size class (Table 3). Bleaching and disease were identified as present or absent. Abrasion effects were not included due to the difficulty in identification of abrasion mortality given turf algae colonization of exposed coral skeletal surfaces during the time elapsed between the storms and the field survey effort (≥ 6 months). Fragments of branching coral (e.g., *Acropora* species) were categorized as either attached to the substrate (attached fragments; e.g., the fragment has wedged into place, or coral tissue has regrown to the substrate to stabilize the fragment in place) or unattached (loose fragments), and categorized as either dead or live (i.e., if live tissue was present). Upside down, overturned, or loose colonies (with at least 20 cm of live tissue) were identified by species and size class.

Table 3. Size categories for coral surveys.

Size category	Size range (cm)
Medium	20 - 50
Large	51 - 100
Extra-large	101-150
Giant	> 150

Due to the stratified random sampling design, area weighting based on the habitat stratification was applied in the analyses for transect survey mean values (i.e., density of damage by region and density of damage by species). Although the sites were allocated based on both habitat and depth, only habitat was used in the analyses weighting due to the limited number of sites in each region and strata. A weighting scheme was not applied to the analysis of roving data, for these sites were selected opportunistically. The Culebra and the NE Reserve/East PR sites were combined for all analyses.

Katie Flynn

Amy Whitt

2. Coral Stabilization

The goal of coral stabilization efforts was to reattach damaged coral fragments and colonies to the reef substrate. This was accomplished by returning coral colonies or fragments to a proper orientation (i.e., upright, live tissue away from the benthos) and securing them to hardbottom reef habitat. Coral reattachment was conducted at sites identified with the highest level of damage by reconnaissance, roving diver surveys, or transect formal assessment surveys. Locations with the highest cost-benefit ratio for fieldwork were prioritized using criteria that included safety of dive operations, site accessibility, transit time, site exposure, and the potential to reattach many corals within a small area versus the within a widespread area.

A team of at least 4 trained divers navigated to the predetermined stabilization site and prepared gear (e.g., crates, lift bags) and materials (e.g., cement, Marmolina™) for reattachment activities. Preparations were based on the expected numbers, sizes, and species of corals to be reattached per site. Appropriate locations with open hardbottom were identified to reattach loose corals to avoid disturbance to undamaged corals. Once in the water, divers distributed themselves around the reef site to begin coral reattachment activities. Corals and fragments were temporarily cached near restoration locations prior to reattachment. The reef surface was cleaned (e.g., turf algae and sediment removed) prior to reattachment to ensure successful adhesion. Cement was used to re-attach corals to the substrate. In locations where the habitat at damaged sites was not suitable for reattaching damaged corals (i.e., substrate reduced to rubble), coral fragments were collected and moved to alternative sites, from 100s of meters up to 3 km distant, which were considered more suitable for the survival of re-attached colonies.

At each coral stabilization site, a brief survey was conducted to describe the hurricane impacts, estimated coral stabilization effort completed, and the need and potential for additional reattachment efforts (Table 4; Appendix C). Descriptive data were collected regarding the size classes (Table 3) and species of corals that were reattached, site GPS coordinates, extent and types of damage observed to the coral and reef, and estimates on how much future coral stabilization effort remained at each site (Table 4). The coral stabilization efforts conducted prior to the FEMA mission included a subset of these descriptors (i.e., site name, location, depth, damage severity, and number of corals stabilized).

Table 4. Classifications used to describe coral stabilization sites.The survey datasheet is in Appendix C.

Site description	Data type
Survey depth (ft)	- Mean depth of surveyed area
Estimated # of at-risk and reattached corals	- Initial # of at risks corals at the site - Number of corals reattached - Number of remaining corals for reattachment - Percent of overall coral stabilization completed at the site
Restoration area covered (m^2)	- Estimated area (footprint) of coral stabilization completed on this date
Restoration area remaining (m^2)	- Estimated area (footprint) for additional coral stabilization on site
Day # for coral stabilization at the site	- Day of reattachment effort at the site (sequential number; e.g., 2 of 2)
Estimated # of days remaining for stabilization at the site	- Number of days remaining to complete coral reattachment at the site
Damage to site	- None - Minor = < 10% damage to corals and reef - Moderate = 10 - 50% damage to corals and reef - Severe = > 50% damage to corals and reef
Additional potential for coral stabilization	- High = > 300 corals to be reattached (> 20cm) = many ESA coral species impacted - Medium = > 100 corals to be reattached (> 20 cm) = some ESA species impacted - Low = < 100 corals to be reattached - No damage
Restoration site potential	- High = significant damage, restoration required for recovery - Medium = moderate damage, might require restoration for recovery - Low = damage present but natural recovery likely - No damage
Stabilized coral species	- List of coral species that were reattached
Coral size class	- Estimate size of corals using size classes (Table 3)

3. Data Visualization

Through the course of this project, two different data dashboards were created using ESRI ArcGIS Dashboard. The initial dashboard was used to facilitate field efforts and communication between the assessment and stabilization teams. During the data collection, a data dashboard was utilized to track the progress of data collection and to provide information flow between teams in near-real-time or as soon as field data were entered (Figure 5). Field assessment data were entered into an online feature service via Survey123 for ArcGIS on the evening of collection or shortly thereafter. These results were automatically ingested into the data dashboard. The data dashboard was used to track effort and plan for the following day's assessment and stabilization activities. Within hours of data collection by the assessment team, stabilization teams were able to quickly identify heavily damaged sites and incorporate them into their field planning efforts. In addition to the dashboard application to support inter-team communication, it was also useful to share the current project status with managers and other decision-makers from multiple agencies.

At the conclusion of the data collection phase of the project, the data collection dashboard was updated to summarize the study results and was integrated into a more comprehensive, publicly-available story map about the project.

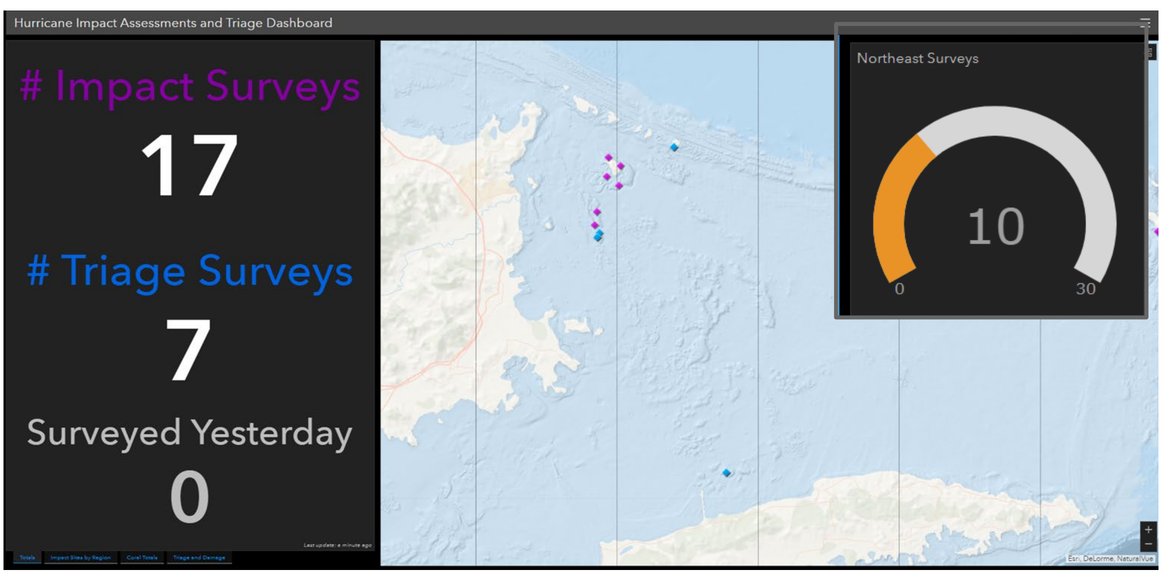


Figure 5. Example of the hurricane impact assessment sample tracking dashboard. This was the initial version of the dashboard that tracked sampling by survey type, presented draft summaries, as well as tallied surveys by region (inset above right). This near real-time dashboard operated for sample tracking and planning; data were accessible to survey teams within 12 hours of collection.

4. Identification of Potential Coral Restoration Habitat near San Juan

Information from the damage assessment and stabilization work was used to design a preliminary plan for potential future coral restoration for the San Juan reefs with the goal of restoring coral habitats and enhancing the wave attenuation benefits of the reefs. *A. palmata w*as identified as the target species for restoration based on two primary factors: 1) the potential habitat for this species within shallow, high-energy reefs, and 2) the potential and feasibility for timely propagation with existing, proven restoration methods. To support this plan, habitat mapping was used to delineate hardbottom reef habitat north of San Juan.

Hardbottom habitat within the selected geographic area was classified with imagery from WorldView - 2 (launched 8 October 2009) and WorldView - 3 (launched 13 August 2014) commercial imaging satellites (www.digitalglobe.com). Both satellites acquire 16-bit data in eight multispectral bands including coastal (band 1 - 0.400 – 0.450 µm), blue (band 2 - 0.450 – 0.510 µm), green (band 3 - 0.510 – 0.580 µm), yellow (band 4 - 0.585 – 0.625 µm) and red (band 5 - 0.630 – 0.690 µm). Both satellites acquire data in 3 additional infrared bands and a panchromatic band; however, due to poor water penetration of light in that area of the spectrum, those bands were not used in this study. The spatial resolution of all satellite images was 2 m. All satellite images were acquired from the National Geospatial Intelligence Agency (NGIA) archive through an agreement between NOAA and NGIA.

Four images were used in the mapping effort (Table 5; Figure 6). Due to persistent cloud, wave, and turbidity issues that obscured benthic habitats, the San Juan study site needed multiple images to create maps for those areas. Of the four images used, only one was acquired after Hurricane Maria. For the San Juan study site, benthic habitats were delineated using spectral classification with the ISODATA (Iterative Self-Organizing Data Analysis Technique) unsupervised clustering algorithm (Jensen 2005) in combination with on-screen, heads-up digitizing.

Table 5. Satellite imagery source and acquisition date used in habitat mapping of hardbottom habitat for potential reef restoration north of San Juan.

Satellite	Image acquisition date
WorldView - 2	February 10, 2013
WorldView - 3	August 22, 2015
WorldView - 3	January 20, 2017
WorldView - 3	September 24, 2017

Figure 7. WorldView – 3 satellite imagery of San Juan, Puerto Rico used in hardbottom habitat mapping. Image acquisition was on January 20, 2017.

To inform the habitat classification, 13 underwater photographs acquired by SCUBA divers were used as ground verification points. All of these photographs from the San Juan study site were acquired on May 1 and 3, 2018. The photos were taken in areas with aggregate reef, pavement, coral rubble, and seagrass.

Based on the feasibility for potential *A. palmata* restoration, depth ranges of 1.5 - 4.5 m were selected from the hardbottom habitats within the footprint of the San Juan potential restoration area. Depth ranges were identified based on the most up-to-date high-resolution LiDAR bathymetry. The area of hardbottom habitat within the potential restoration site was calculated using ArcGIS.

The hardbottom habitat map was used to calculate the restorable footprint area by subtracting areas unsuitable for restoration. The proportion of the hardbottom area occupied by other organisms and natural sand channels was estimated from field observations during assessment, restoration, and habitat classification dives; as well as from past experience designing large-scale coral restoration projects elsewhere in Puerto Rico. The restorable area value was used to determine the number of corals that would need to be propagated and outplanted to meet the goal of restoring *A. palmata* at a density of one coral per m^2.

RESULTS

1. Assessment

A total of 147 of the targeted 150 assessment sites were completed in 38 field days between February 27 and May 7, 2018 (Figures 7a, b; Appendix D). Weather and water visibility constraints were limiting factors for in-water field days. Divers surveyed a total of 414,354 m^2. This included 11,300 m^2 in transect assessment surveys (n = 147) and 403,054 m^2 (n = 143) in roving diver assessment surveys. A total of 87,761 corals were counted by the assessment team. This included 28,791 corals assessed in transect surveys, and 58,970 corals in roving diver surveys. Observed damage included coral colony abrasion, breakage, dislodgement, and overturning (Figure 8).

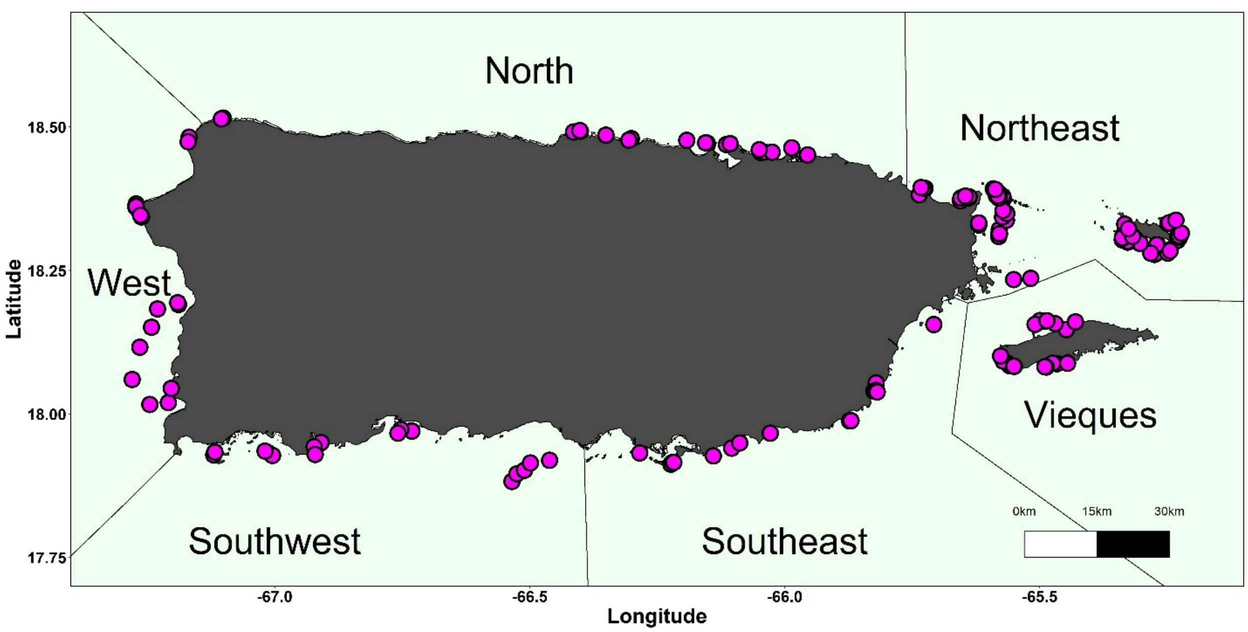


Figure 8a. Locations of coral assessment sites around Puerto Rico.

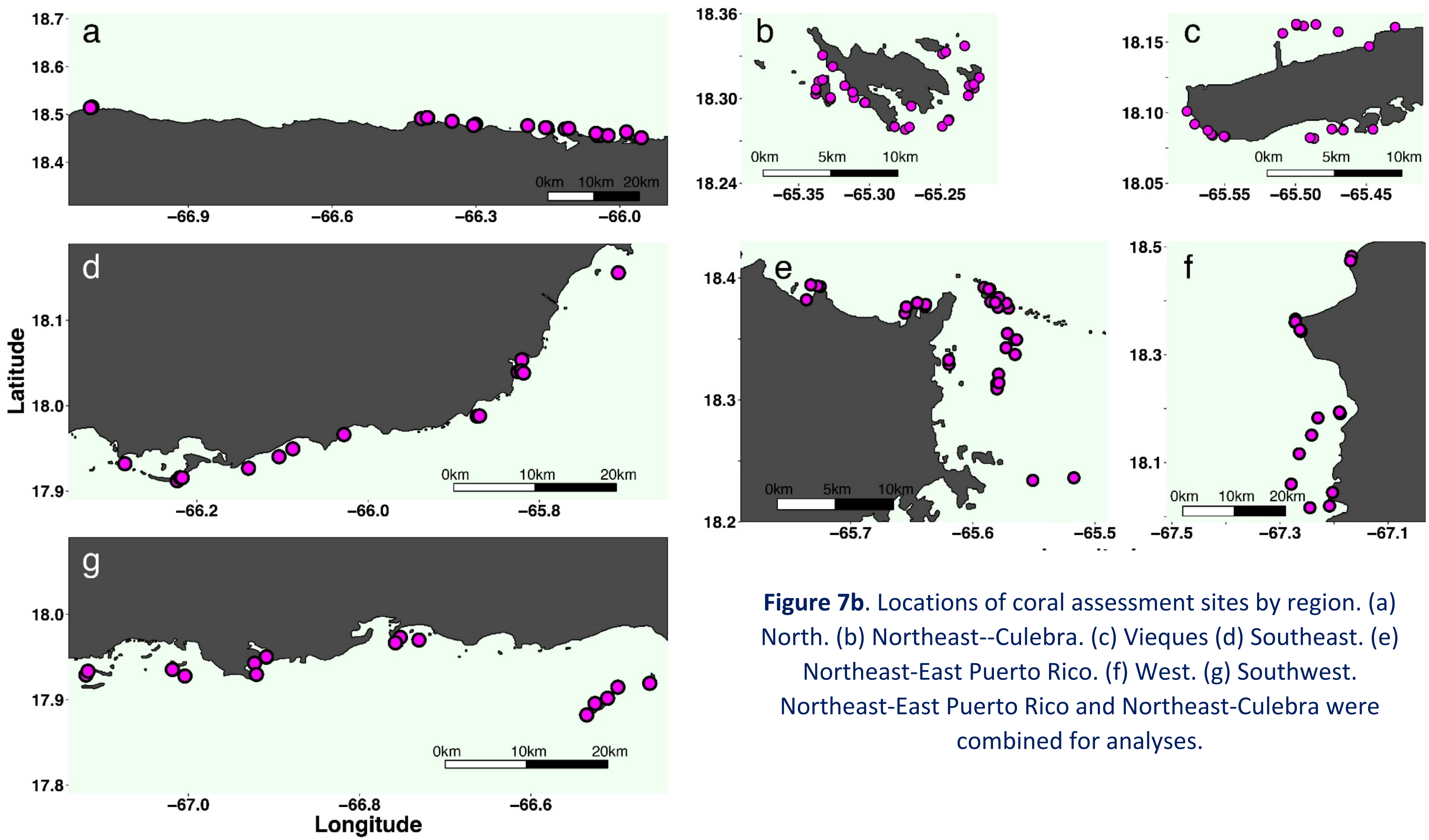


Figure 7b. Locations of coral assessment sites by region. (a) North. (b) Northeast--Culebra. (c) Vieques (d) Southeast. (e) Northeast-East Puerto Rico. (f) West. (g) Southwest. Northeast-East Puerto Rico and Northeast-Culebra were combined for analyses.

Figure 9. Observed damage to reefs surveyed ir post-hurricane assessments. Examples include (a) broken reef, damaged colonies, and fragments of *Acropora palmata*, (b) broken reef and dislodged lobes of *Orbicella annularis*, (c) sheared pillars of *Dendrogyra cylindrus*, (d) a thicket of branching *Porites* species broken up into loose rubble partially covered by macroalgae, (e) fragments of broken *A palmata* and *Acropora cervicornis*, and (f) a large colony of overturned, loose *O. annularis*.

1.1. Summary by Region

Region-wide results for transect assessment surveys indicated that the Northeast and Vieques regions showed the highest number of damaged corals, as quantified by number of damaged corals (Figure 9) and mean density of damaged corals (Figure 10). Region-wide results for the roving diver assessment surveys, which specifically targeted reef areas that may have had impacts outside of the assessment transect area, showed the highest prevalence of damaged colonies (percentage of total colonies with damage) in the Northeast, North, Vieques, and West regions (Figure 11).

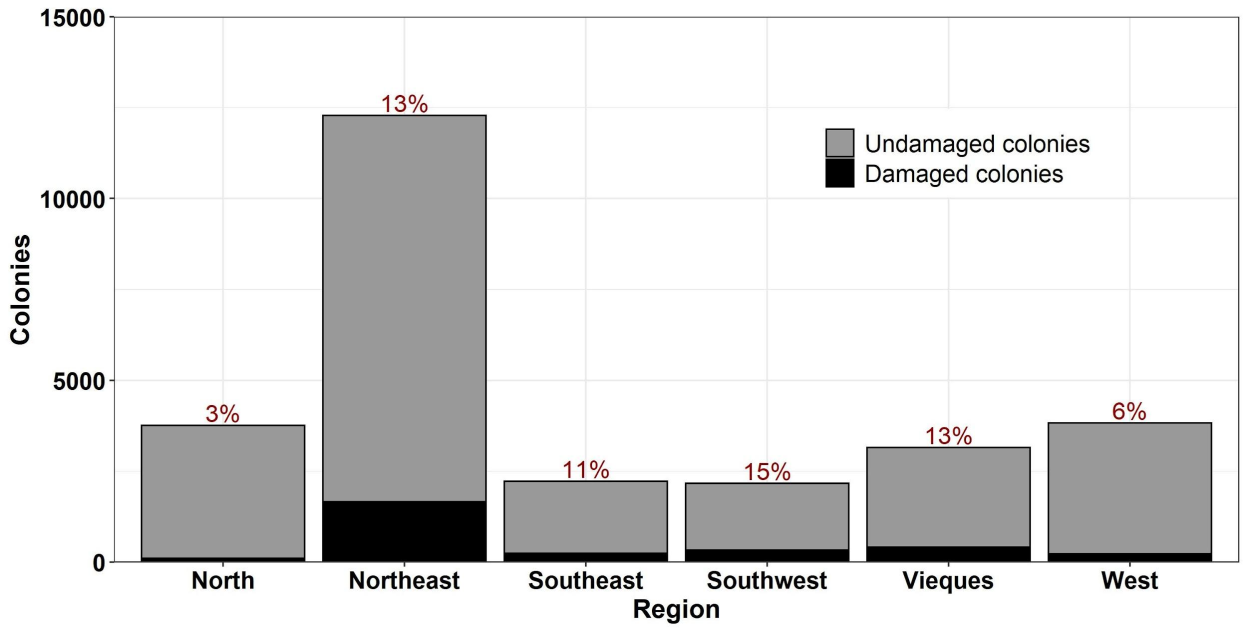


Figure 10. Regional comparison of damaged and undamaged colonies based on transect assessment surveys. Values in red indicate the prevalence of damaged colonies. The northeast region had the highest number of both undamaged and damaged corals.

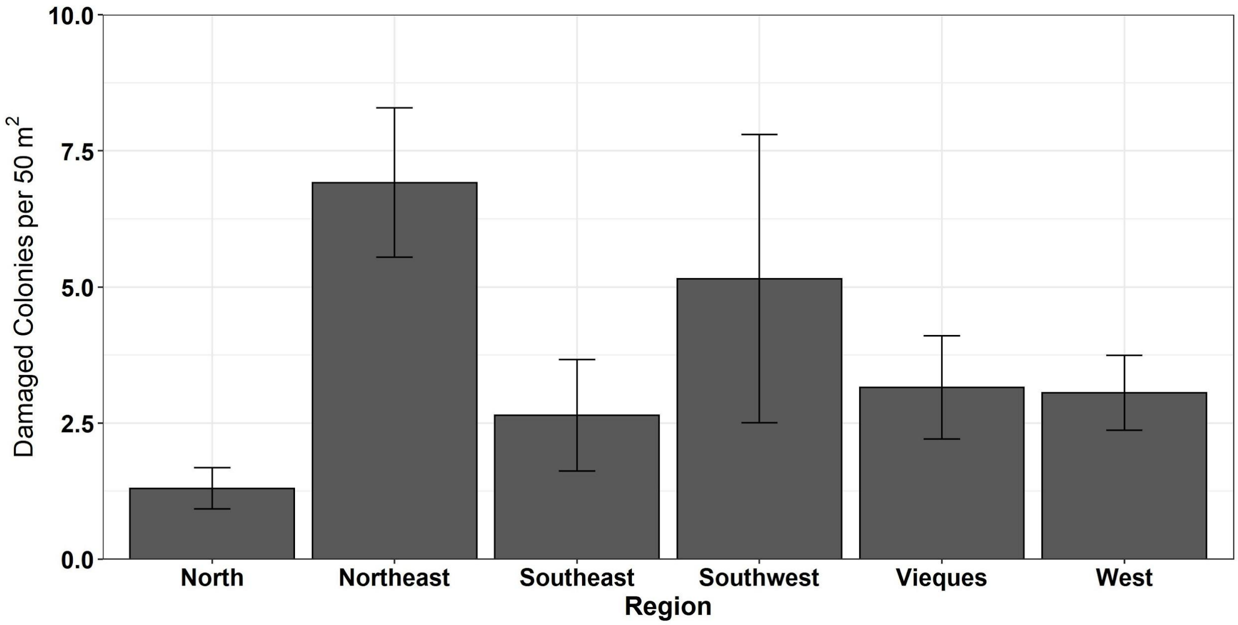


Figure 11. Regional comparison of mean density of damaged corals (colonies per 50 m^2) based on transect assessment surveys. Error bars represent standard error.

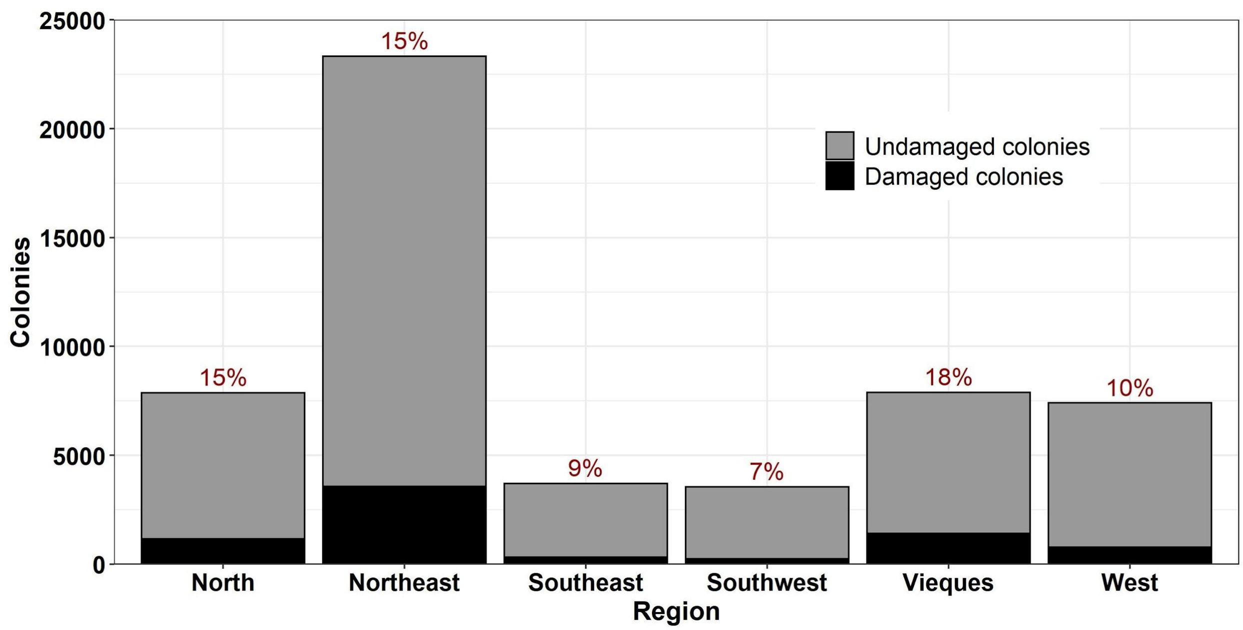


Figure 12. Regional comparison of damaged and undamaged colonies based on roving assessment surveys. Values in red indicate the prevalence of damaged colonies. The northeast region had the highest number of both undamaged and damaged corals.

1.2. Summary by Size and Species

For coral reefs off of Puerto Rico, 10% (2,958 of 28,791) of coral colonies in transect surveys were broken, overturned, upside down, or loose (Appendix E). In roving surveys, 12% (7457 of 58,970) of colonies were damaged (Appendix F). Large (50 - 100 cm) and extra-large (100 - 150 cm) coral colonies had the greatest proportion of damage to colonies (15%; Figure 12). Medium-sized coral colonies (20 - 50 cm) had the highest frequency of occurrence as well as the largest number of damaged colonies.

Figure 13. Size classes of coral colonies with damage in transect assessment surveys. Values in red indicate the prevalence of damaged colonies. The most numerous colonies surveyed were in the medium size class (20-50 cm). Fewer large (50-100 cm) and extra-large (100-150 cm) colonies were surveyed, but corals within these size categories had the greatest proportion of damaged colonies.

Damage varied by coral species (Figure 13). *Dendrogyra cylindrus* (pillar coral) sustained the highest frequency of occurrence of damage (77% of 117 colonies showed damage), followed by the branching *Porites* species (finger corals): *P. porites*, *P. divaricata*, and *P. furcata* (47% of 942 colonies showed damage), *A. palmata* (elkhorn coral; 45% of 421 colonies showed damage), *O. annularis* (lobed star coral*;* 43% of 1548 colonies showed damage), and *Acropora cervicornis* (staghorn coral; 38 % of 165 colonies showed damage). All of these species, except those in the genus *Porites*, are listed as Threatened under the ESA. The coral species with the highest frequency of occurrence, *Porites astreoides* (mustard hill coral) and *Pseudodiploria strigosa*

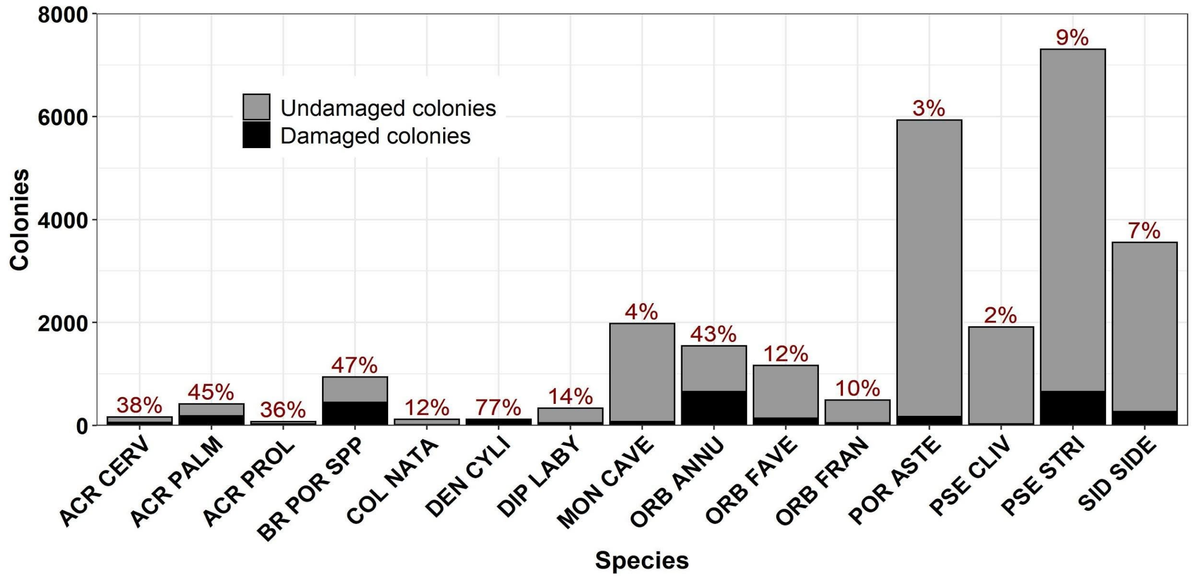


Figure 14. Damage by coral species counted in transect assessment surveys. Red values indicate damage prevalence. Species names and abbreviations are in the Species Abbreviations.

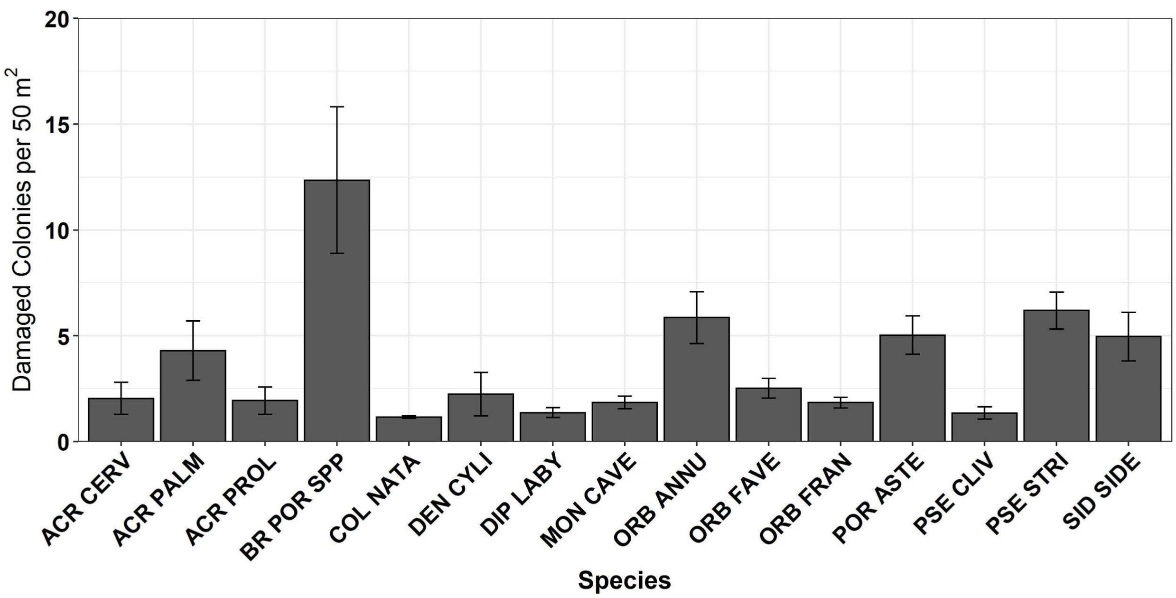


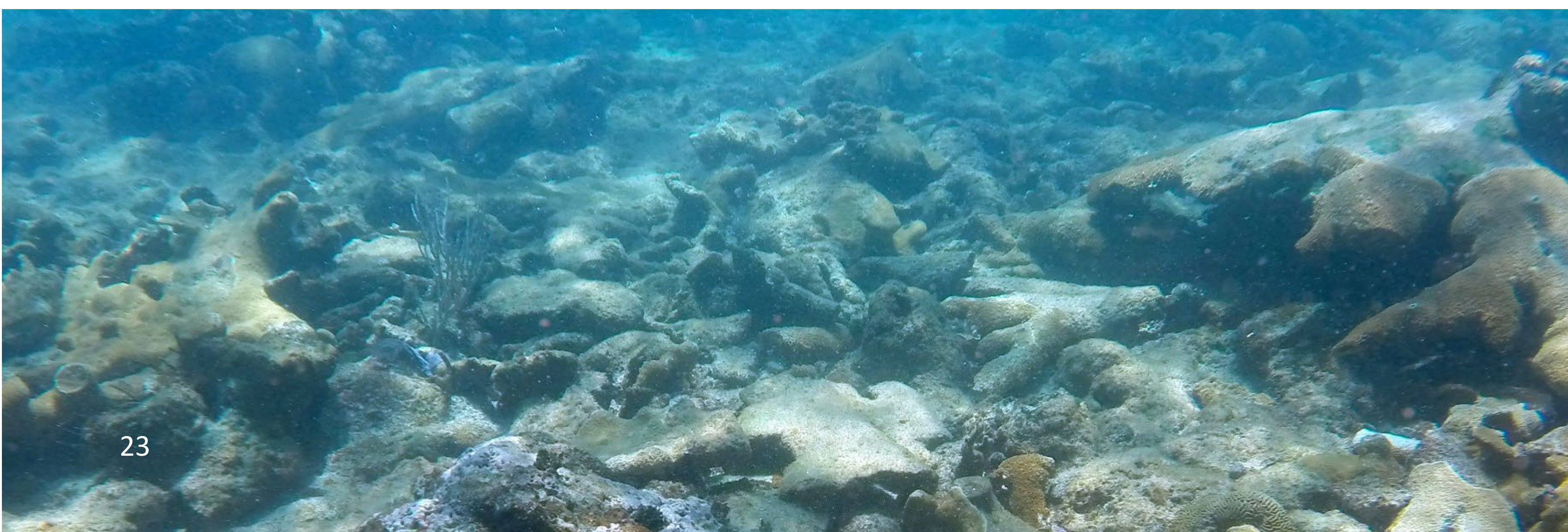
Figure 15. Mean density of damaged colonies by species in transect assessment surveys. Density is shown as coral colonies per 50 m^2. The highest densities of damaged colonies were in branching *Porites* species (finger coral; BR POR SPP), *Pseudodiploria strigosa* (symmetrical brain coral; PSE STRI), and *Orbicella annularis* (lobed star coral; ORB ANNU). Error bars represent standard error. Species names and abbreviations are in the Species Abbreviations. Additional information is in Appendix E.

(symmetrical brain coral), had a low prevalence of damaged corals (3% and 9%, respectively), although *P. strigosa* had a high number of damaged colonies). Branching *Porites* species had the highest density of damage (number of damaged colonies per 50 m^2; Figure 13), followed by *P. strigosa* and *O. annularis*. Additional information is in Appendix E.

Overall, 1,380 coral fragments were counted during transect assessment surveys (Appendix E). Of these, 994 were *A. palmata* (72%), 174 were branching *Porites* species (13%), 151 were *A. cervicornis* (11%), 46 were *A. prolifera* (3%), and 14 (1%) were *D. cylindrus*, and 1 *O. annularis* (less than 1%). These species also showed both high prevalence and high density of damage on attached colonies. In roving assessment surveys, an additional 5,234 fragments were counted (Appendix F). Of these, the majority were *A. palmata* (3,967; 77%), 713 were *A. cervicornis (*14%), 305 were branching *Porites* species (6%), 215 were *A. prolifera* (4%), 30 were *D. cylindrus* (>1%), and 4 were *O. annularis* (>1%).

1.2.A. Damage to *Acropora palmata*

Acropora palmata damage was evident on thickets around Puerto Rico (Figure 8). Because this reef-building coral species is a primary contributor to attenuate nearshore wave energy and is listed as a Threatened species, some additional analyses were conducted to identify geographic areas with the most damage. Damage for *A. palmata* was categorized as severe at a site where more than 100 damaged corals and fragments were surveyed (including both transect and roving surveys), moderate where 50-99 damaged corals and fragments were surveyed, and minor damage was defined as fewer than 49 damaged corals or fragments. Damage categories were classified based on the species-specific statistical distribution of the number of colonies with damage for all sites with damage. A total of 14 sites were categorized with severe damage to *A. palmata*. These sites were located in the Northeast (including Culebra), North, and West regions (Figure 15). Two of the five sites (Figure 16) with the highest levels of damage are north of San Juan (Dominoes 1 and 2) and one is east of Fajardo (NE_537), both of which are cities with significant coastal infrastructure investment. Damaged and undamaged reef in Dominoes 1 and 2 are shown in SfM photomosaics (Figures 17, 18; Table 6). Additional details on damaged corals at these five sites are provided in Appendix G.



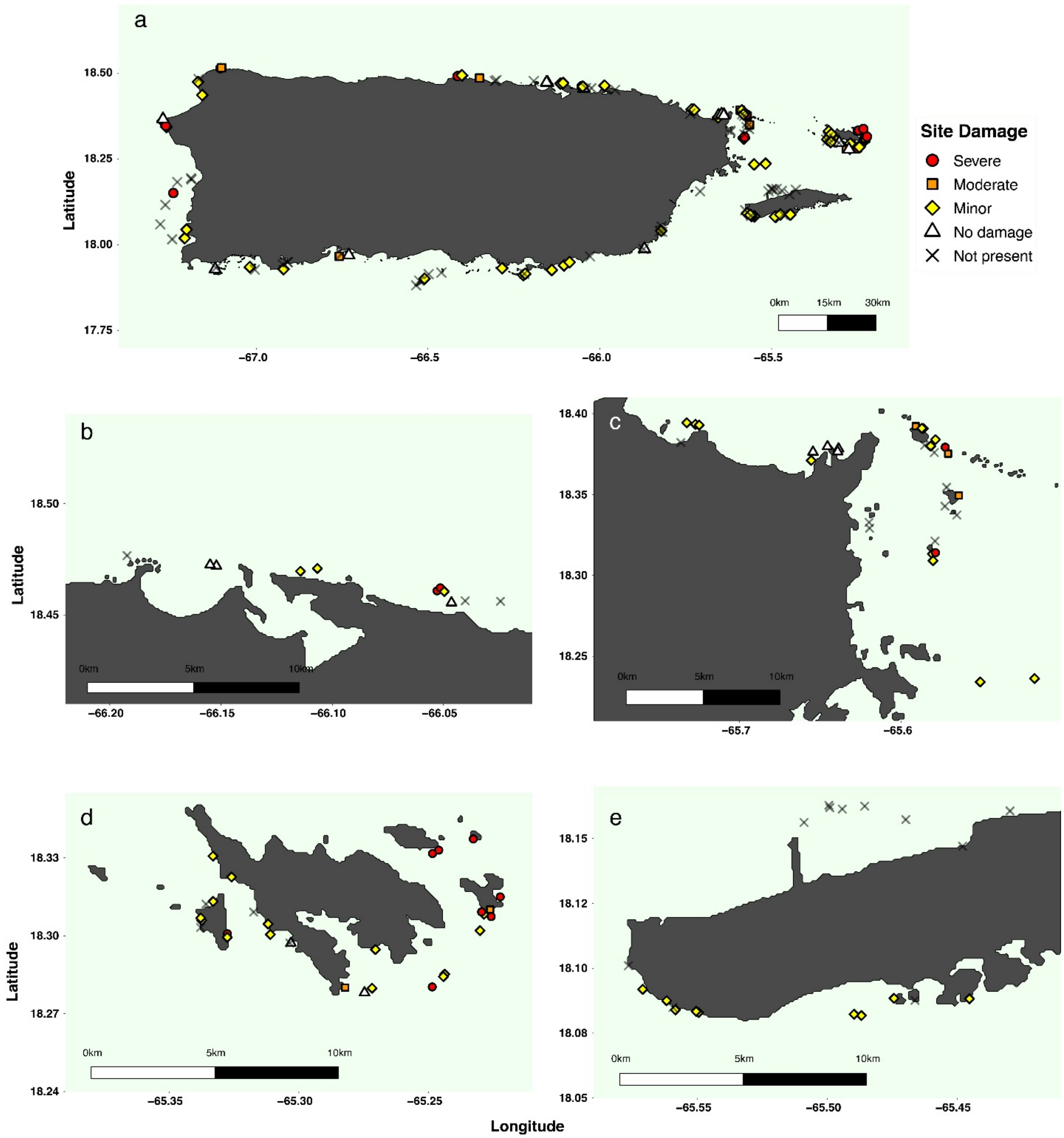


Figure 16. Damage to *Acropora palmata* at all survey locations around Puerto Rico. (a) Severe damage (red circles) was defined as more than 100 broken colonies and fragments at a site. Moderate damage (orange squares) was defined as a site with 50-99 broken colonies and fragments, and minor damage (yellow diamonds) was defined as a site with 49 or fewer broken colonies and fragments. Sites with no damage (white triangle) or where *A. palmata* was not present (black 'X's) are also indicated. A total of 14 sites were categorized with severe damage. Panels (b-e) show (b) damage to *A. palmata* in the San Juan area, (c) Northeast – East Puerto Rico, (d) Northeast – Culebra, and (e) Vieques.

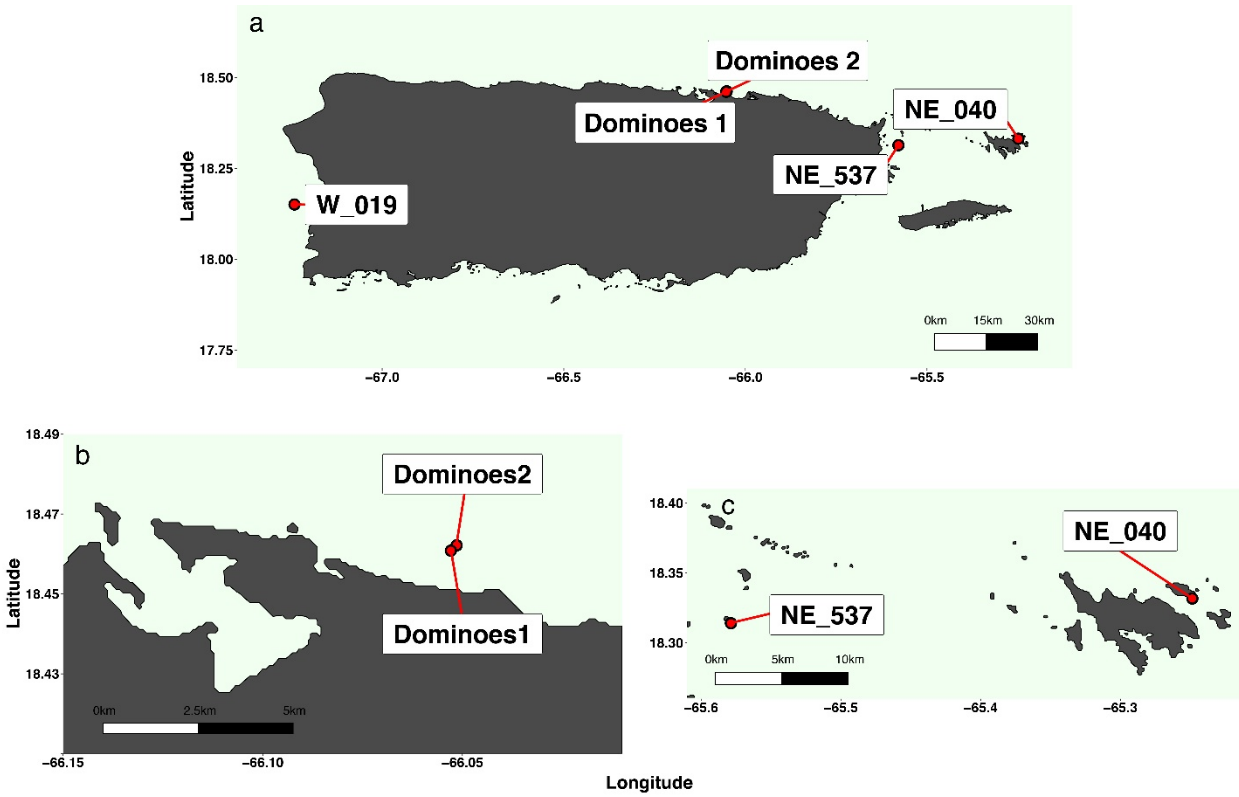


Figure 17. The five survey sites with the most severe damage to *Acropora palmata.* (a) Extent of the assessment survey, (b) the San Juan area and (c) Northeast region.Additional information on these sites is in Appendix G.

Table 6. Location and damage classification of Structure from Motion imagery collection sites.

Site name	Damage classification	Coordinates (Latitude)	Coordinates (Longitude)
Dominos Plot 1	Colony breakage	18.46164	-66.05159
Dominos Plot 2	No breakage	18.46263	-66.05243

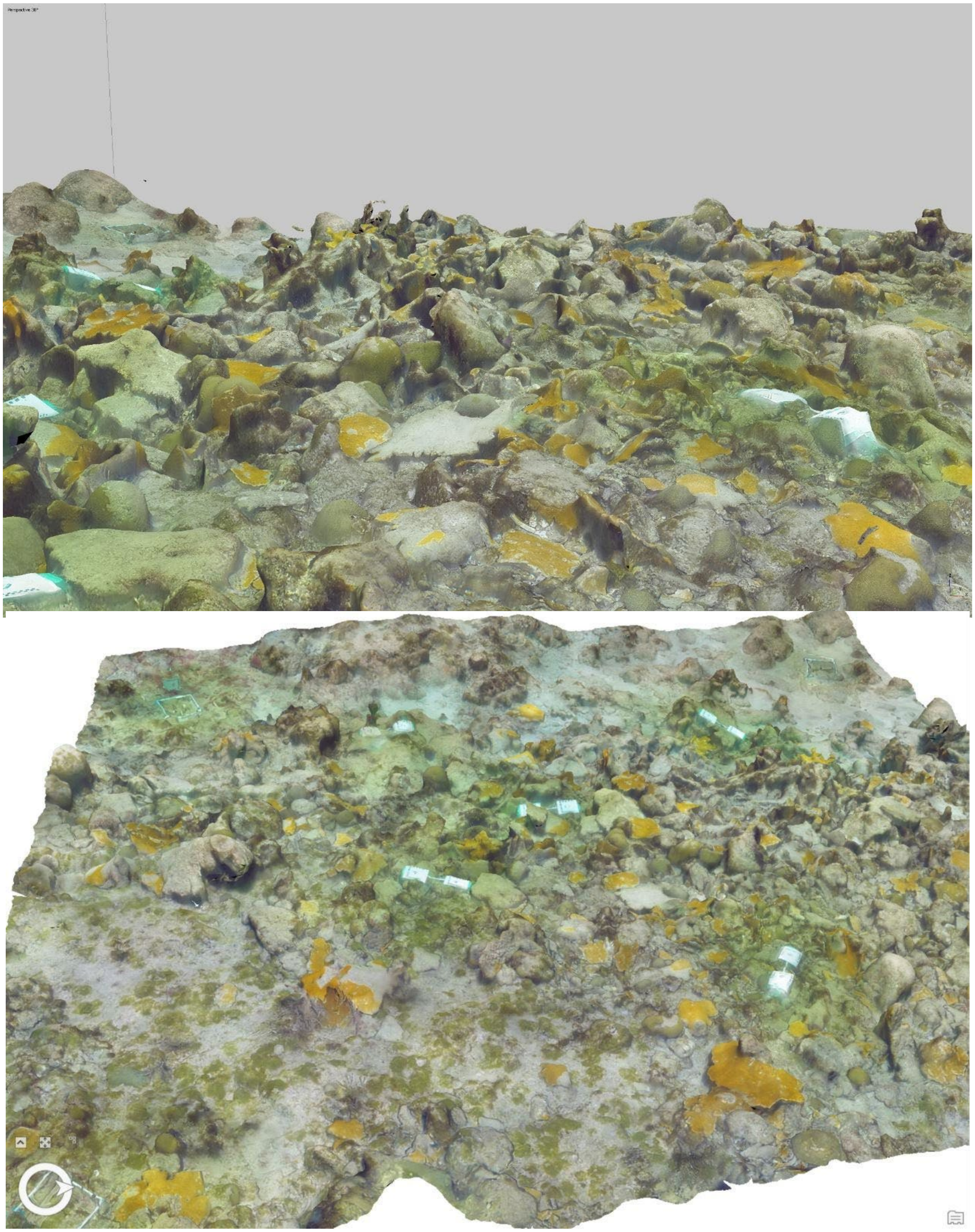


Figure 18. Seascape photomosaics for Dominos 1 damaged reef.The top image shows a side view, and the bottom image shows an oblique top view.

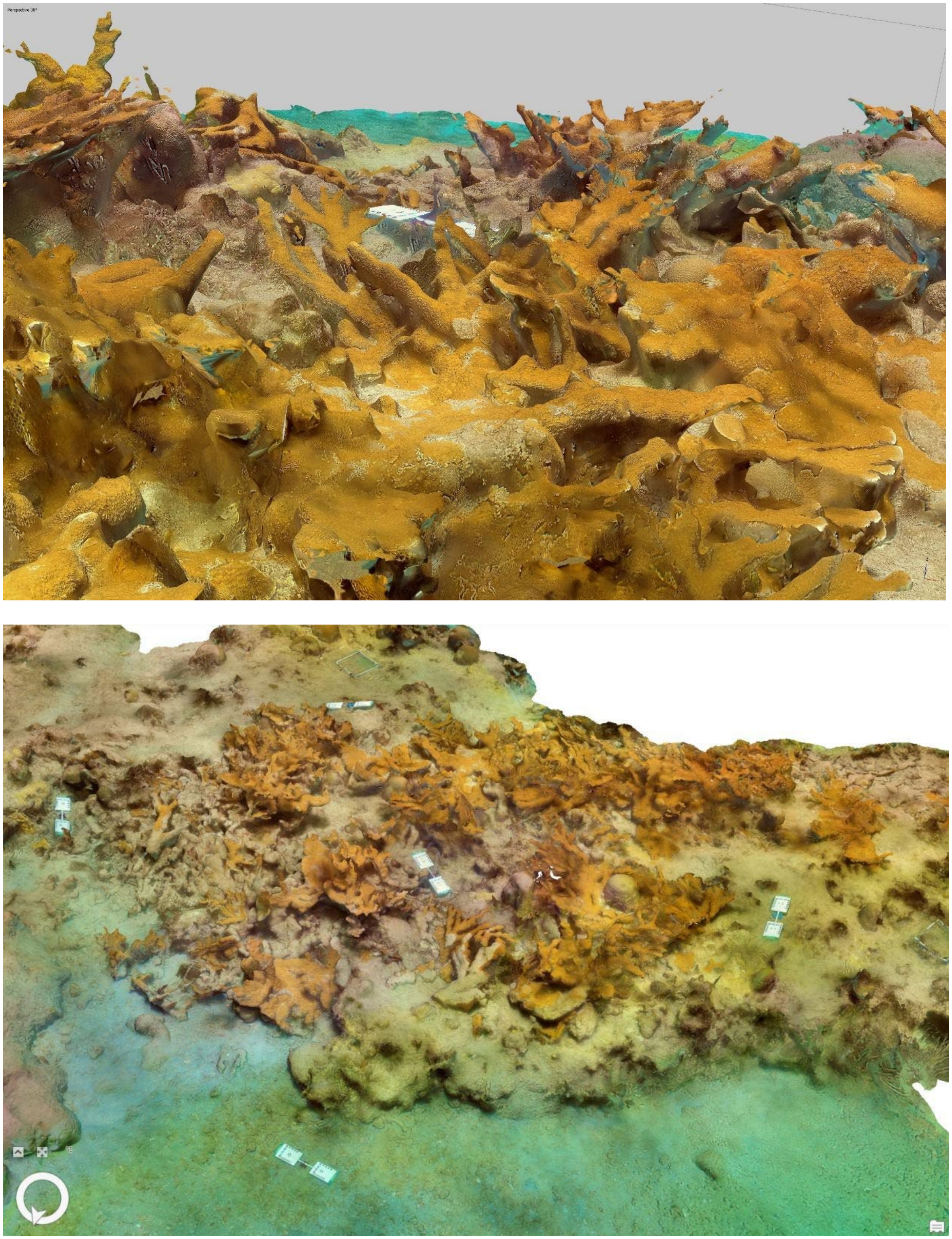


Figure 19. Seascape photomosaics for Dominos 2 undamaged reef. The top image shows a side view, and the bottom image shows an oblique top view.

1.2.B. Damage to *Orbicella annularis*

Orbicella annularis damage (Figure 8) was most concentrated around Culebra. Because this reef-building coral species is a primary contributor to attenuate nearshore wave energy and is listed as a Threatened species, some additional analyses were conducted to categorically rank geographic areas with the most damage. Damage for *O. annularis* was categorized as severe at a site where more than 100 damaged corals and fragments were surveyed, moderate where 50-99 damaged corals and fragments were surveyed, and minor damage was defined as fewer than 49 damaged corals or fragments (Figure 19). Damage categories were assigned based on the statistical distribution of the damage per site specific to this species. A total of 5 sites were categorized with severe damage; these sites were located around Culebra in the Northeast regions (Figure 20). Additional details on damaged coral species at these five sites are provided in Appendix H.

Katie Flynn

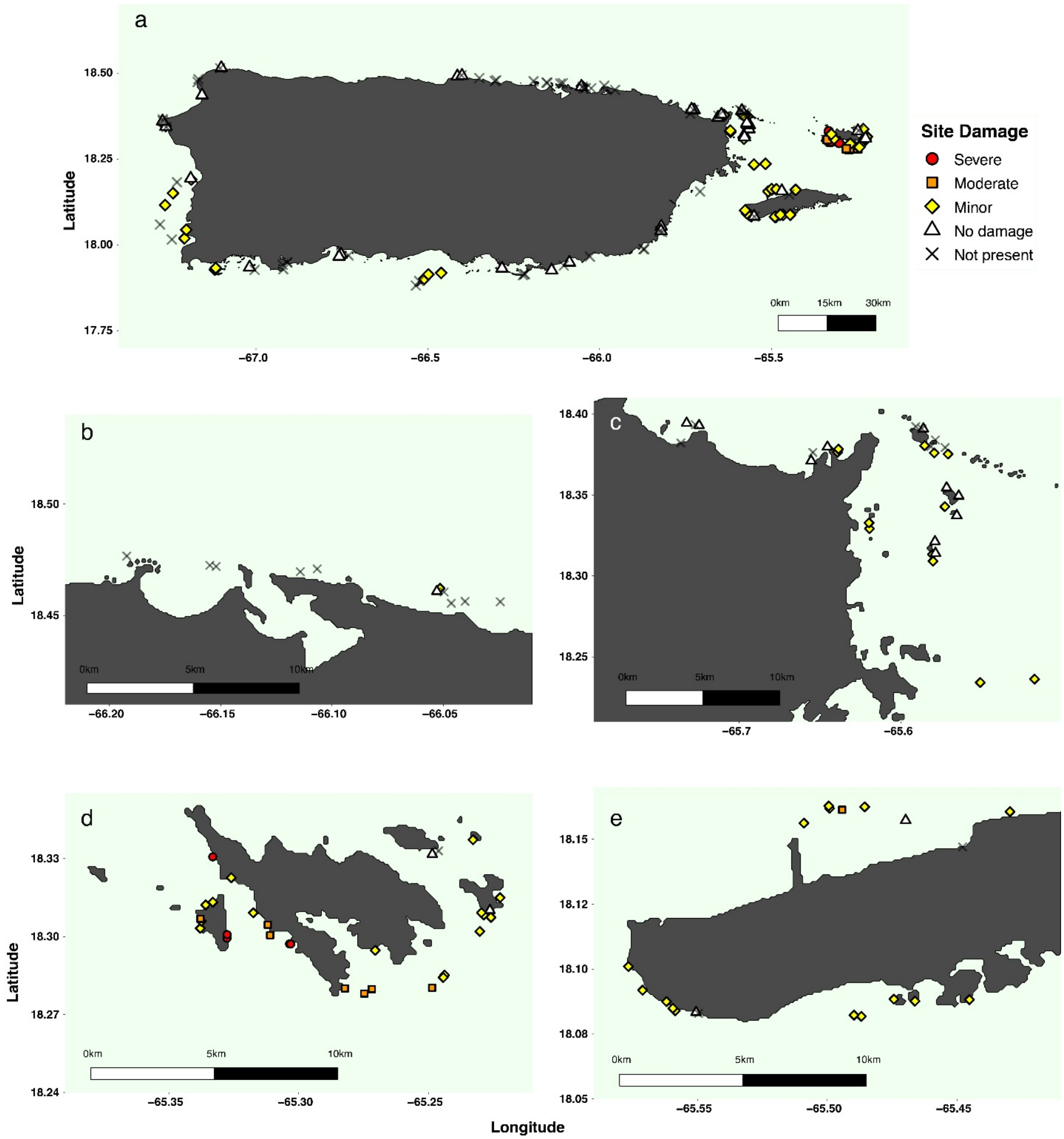


Figure 20. Damage to *Orbicella annularis* (lobed star coral) at all survey locations around Puerto Rico.(a). Severe damage (red circles) was defined as more than 100 broken colonies and fragments in transect and roving surveys combined. Moderate damage (orange squares) was defined as 50-99 broken colonies and fragments, and minor damage (yellow diamonds) was defined as 49 or less. Sites with no damage (white triangles) or where *O. annularis* was not present (black 'X's) are also indicated. The 5 sites with the most severe damage were all near Culebra. Insets show damage to *O. annularis* in (b) the San Juan area, (c) Northeast – East Puerto Rico, (d) Northeast – Culebra, and (e) Vieques.

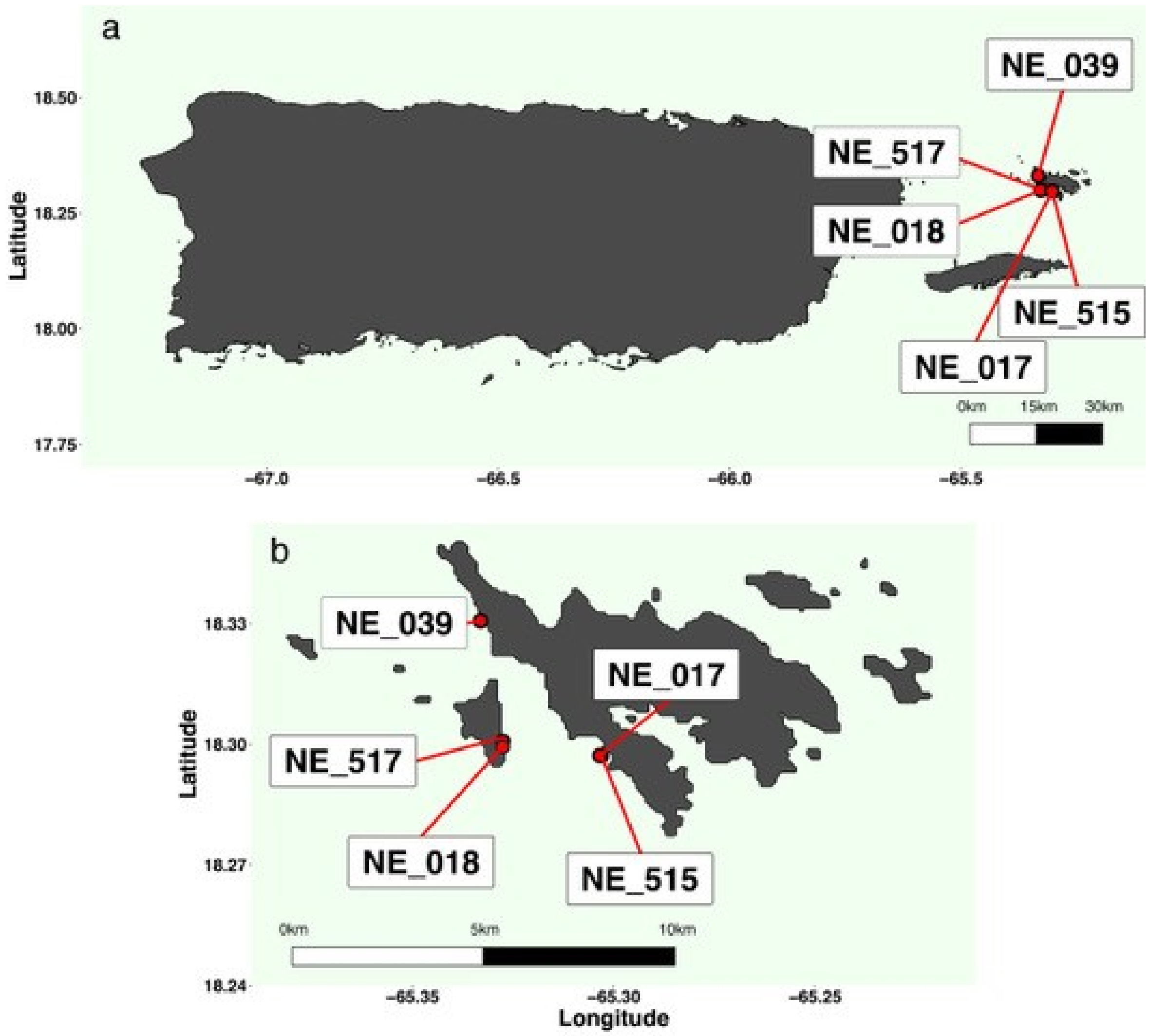


Figure 21. The five survey sites with the most severe damage to *Orbicella annularis*. (a) Extent of the Puerto Rico assessment area, and (b) the most severe damage was observed around Culebra. Additional information on these sites is in Appendix H.

1.3. Archipelago-wide Impacts

Overall mean density of coral damage off of the archipelago of Puerto Rico as a whole was 3.5 corals per 50 m^2. Although this may not seem to be a major impact on a small scale, when extrapolated out to the entire region, this could mean over 900,000 damaged or broken corals in depths up to 7 m. Archipelago-wide mean coral density was 28.3 corals per 50 m^2, which would indicate the potential for 7.4 million corals in the sampling domain. It is possible that the actual damage to Puerto Rico's reef was much higher than 11%, for surveys within this study included less than 1% of the shallow (less than 7 m depth) reef area.

2. Coral Stabilization

In Puerto Rico and the USVI, all sites selected for coral stabilization were identified to have had severe damage (> 50% damage to corals and reef) and one or more of the following: large numbers of fragments with living coral tissue or loose colonies detached from the substrate (Figure 21). Coral reattachment efforts focused mainly on the following reef-building species: *A. palmata*, *Colpophyllia natans*, *D. cylindrus*, *Diploria* spp., *Orbicella* spp., *P. astreoides* and *Pseudodiploria* spp. (Figure 22).

Across all efforts and locations, over 16,000 corals were reattached at 63 sites (Appendix I). This work required over 100 field days conducted between September 2017 and July 2018 with multiple groups in different geographic regions. In the pre-FEMA coral stabilization, 5,577 corals were reattached at 21 sites in Puerto Rico and 2,005 corals were reattached at 7 sites in the USVI. As a result of the FEMA mission in Puerto Rico, an additional 8,727 corals were reattached at 35 reef sites.



3. Data Visualization

A project summary and overview was created in ArcGIS Online as a StoryMap and Dashboard (Figure 23). This interactive website provides a project overview and a high level data summary with spatial and temporal components. In addition, the website provides access to data and images. The intended audience for this product included managers, researchers, restoration practitioners, and the general public. The Dashboard is publicly available online. All data are publicly available via 1) NOAA NCEI Accession Number 0221189 (Viehman et al. 2020), and 2) links within the online StoryMap.

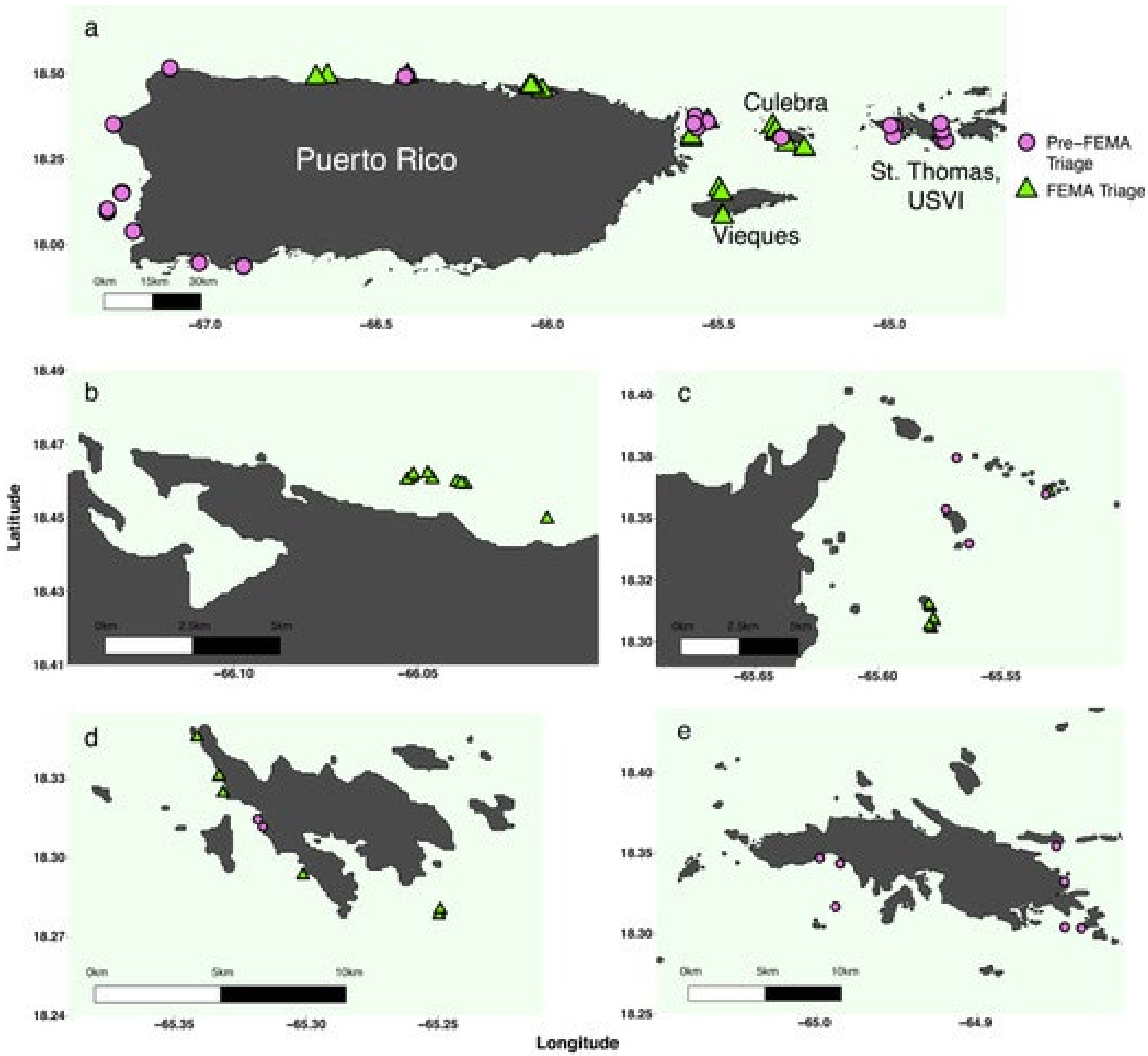


Figure 22. Sites where corals were reattached in Puerto Rico and the U.S. Virgin Islands. (a) Green triangles indicate sites where corals were reattached as part of the FEMA mission assignment to NOAA, and purple circles indicate where corals were reattached using NOAA and NFWF funding. Insets include (b) coral reattachment sites in the San Juan area, (c) Northeast – East Puerto Rico, (d) Northeast – Culebra (d), and (e) St. Thomas, USVI.

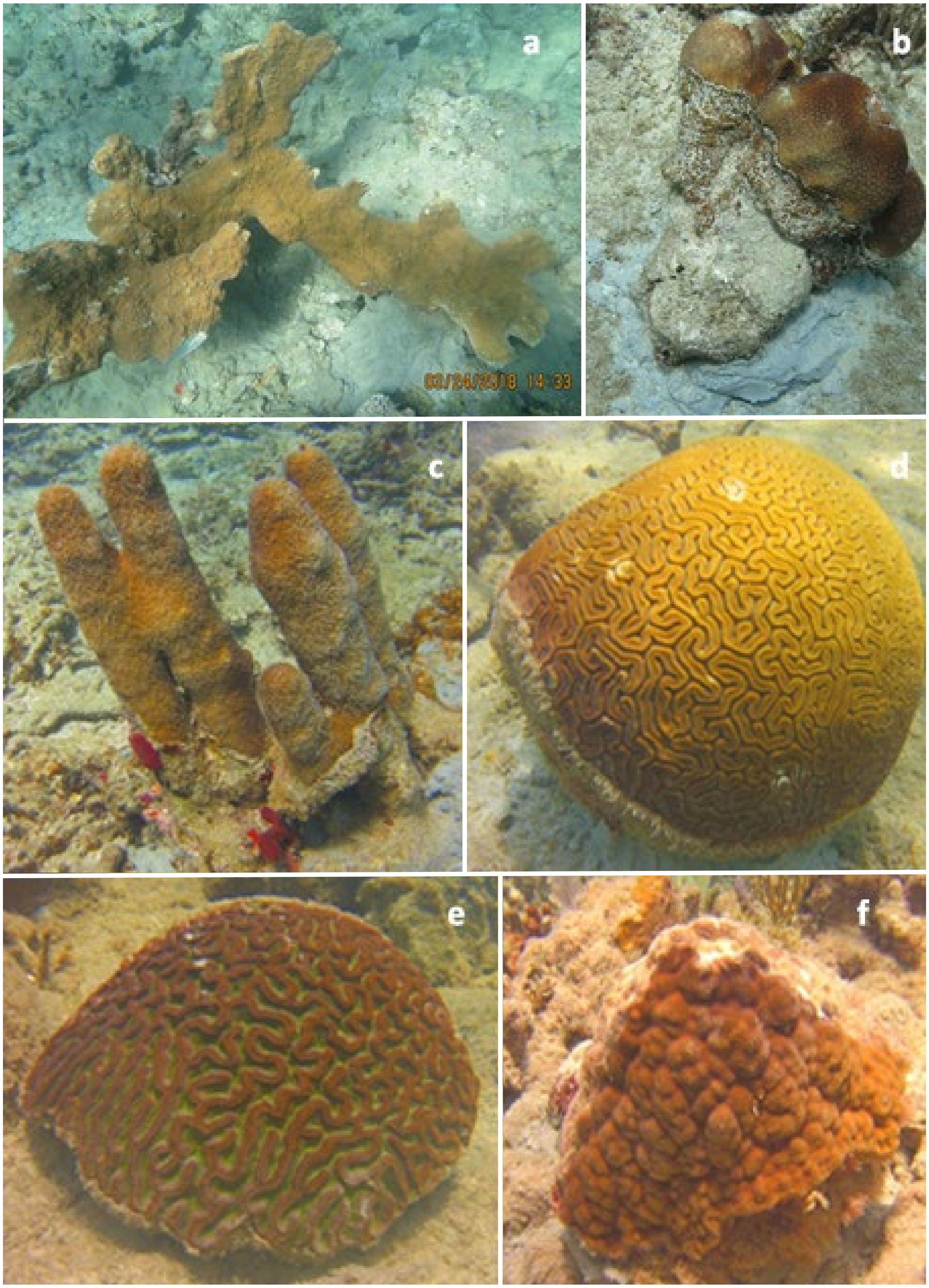


Figure 23. Primary coral species reattached by the stabilization team.(a) *Acropora palmata* (elkhorn coral); (b) *Orbicella annularis* (lobed star coral); (c) *Dendrogyra cylindrus* (pillar coral); (d) *Diploria labyrinthiformis* (grooved brain coral); (e*) Colpophyllia natans* (boulder brain coral); (f) *Porites astreoides* (mustard hill coral).

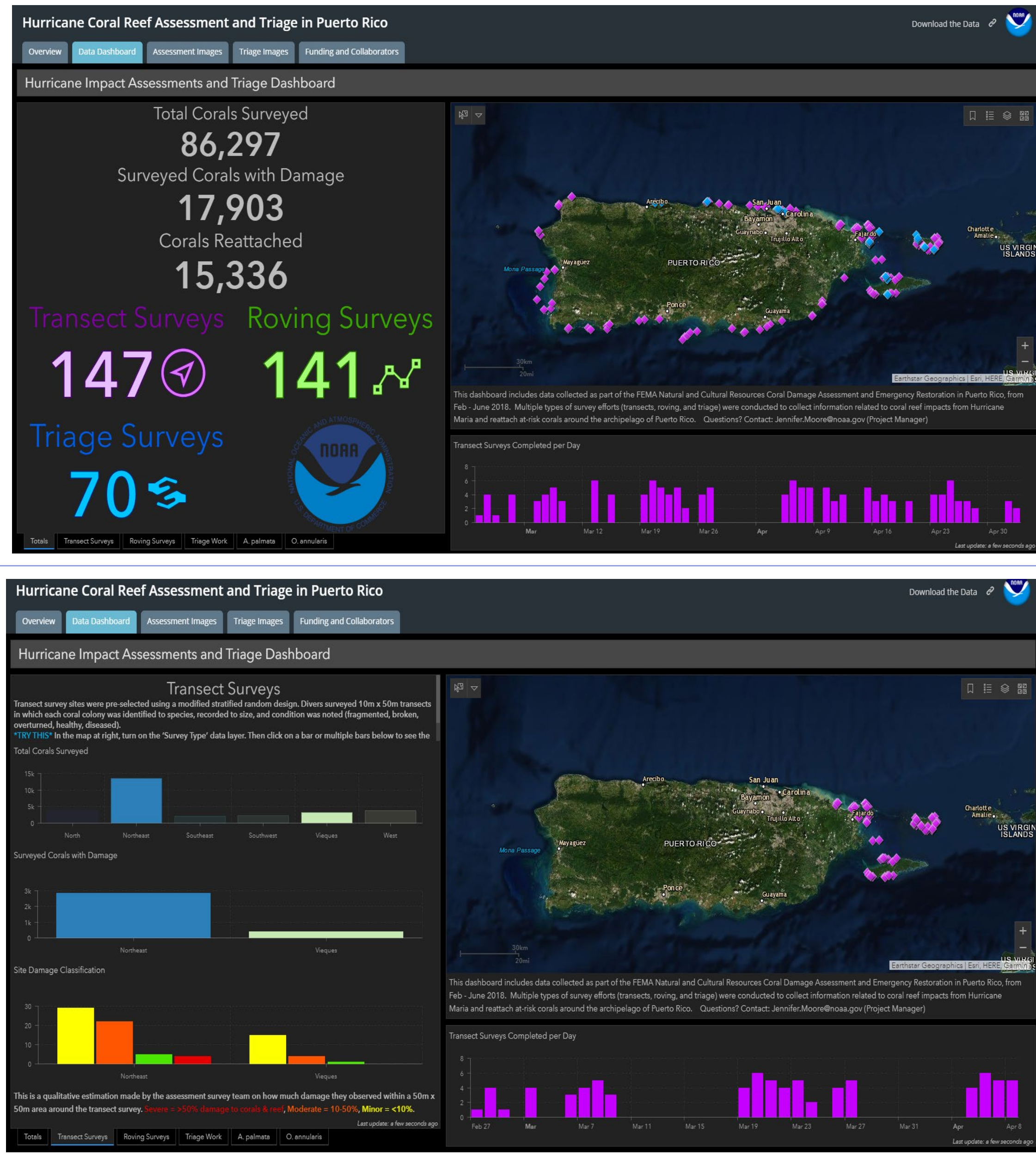


Figure 24. The data dashboard section of the story map.Each section of the dashboard is interactive, which allows a user to highlight specific data of interest. (Top panel) Highlight of summary statistics as well as daily effort (map and chart at bottom right). Additional sections are dedicated to each survey effort. (Bottom panel) Transect assessment results. For example, with a few clicks only the Northeast and Vieques regions are visible (bottom image) in the transect assessment charts and in the map at right. Other sections of the story map provide details on the project summary, partners, as well as underwater images from the assessment and stabilization efforts.

4. Identification of Potential Restoration Areas

The mapped hardbottom habitat between 1.5-4.5 m depth within the reef complex north of San Juan totaled over 2 million m^2 (Figure 24, Table 7). Because the mapped hardbottom area includes a portion of habitat that is currently occupied by other organisms and natural sand channels, assumptions were made to estimate the actual reef area deemed potentially restorable. Calculating the potential restoration area was an initial step in developing a restoration plan for the San Juan reef system, a process which continued at the time of publication.

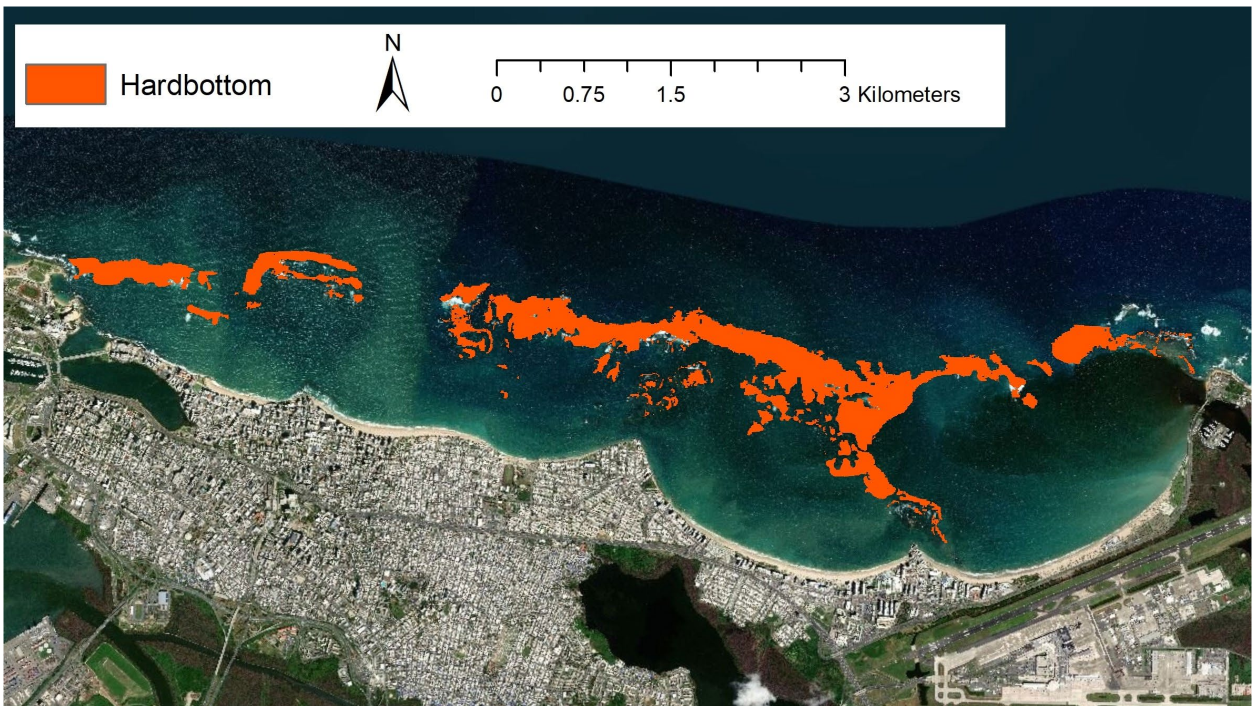


Figure 25. San Juan study site with mapped hardbottom habitats shown in orange. Satellite imagery sources in image: E, DigitalGlobe, GeoEye, Earthstar Geographics, CNES, Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Table 7. Adjustments made to the mapped hardbottom area to determine the potential restorable area of the San Juan reef for future restoration planning.

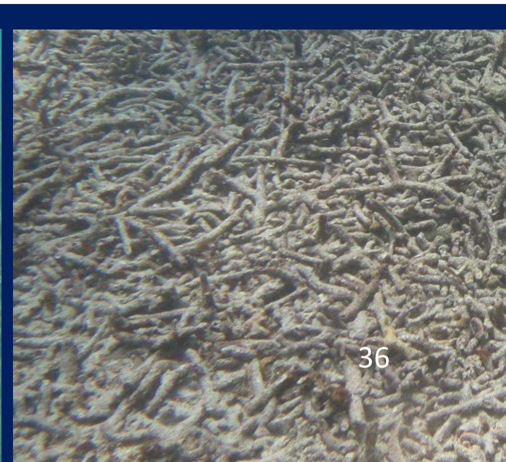
Mapped hardbottom area (m^2)	30% reduction to account for sand channels (m^2)	25% reduction for unsuitable habitat (m^2)	30% potential restorable area (m^2)
2,104,030	1,472,821	1,104,616	331,385

DISCUSSION

High wave energy from Hurricanes Irma and Maria caused extensive breakage and fragmentation to nearshore *A. palmata, O. annularis* and the branching *Porites* species in multiple geographic regions of Puerto Rico, from the west coast along the north coast to the northeast, as well as Culebra and Vieques. Although several of the most impacted species reproduce asexually through fragmentation and can benefit from fragmentation (e.g., Lirman 2000), fragments are more likely to develop into healthy adult colonies if reattached to the substrate (Griffin et al. 2015). Therefore, for degraded reefs, restoration efforts contribute to maintaining or improving the capacity of these nearshore shallow water reefs systems that protect coastal infrastructure.

Assessment surveys showed reef damage consistent with areas that likely experienced highest wave energy during the passage of the hurricanes. Based on the random transect surveys, coral reef sites that experienced the most severe damage were found in the Northeast (including Culebra), North, Vieques, and West regions. Although the Southwest region had the highest damage prevalence (15%), this was likely due to 1) the lowest number of corals observed in the Southwest region relative to other regions, and 2) a single site with high levels of damage to branching *Porites* species (94 broken, overturned, or loose colonies surveyed). Based on the roving diver surveys, which were specifically targeted to find damage, the Northeast, North, Vieques, and West regions all sustained approximately twice the amount of damage than the Southeast and Southwest. Within a region, sites experienced varying levels of damage. This may be based on the wave exposure (i.e., depth and/or orientation with respect to the dominant wave direction) and coral species, abundance, and morphology at a site. For example, corals with branching and lobed morphologies had the highest frequency of occurrence for damage. Coral species with low-profile morphologies (e.g., *P. astreoides* and *Pseudodiploria clivosa*) with lower exposure to wave energy dominated sites that had no damage or minor damage.

As detailed above, thousands of fragments and colonies of these species were reattached to the reef; however, it is likely that thousands more detached corals were not reattached and did not survive. The work summarized here was completed prior to July 2018 at the termination of



funding. However, in March 2019, another 1,200 corals were reattached in Culebra, Puerto Rico by the NOAA Restoration Center as part of a project for addressing physical impacts on coral reefs. This stabilization effort took place 18 months after the storms had originally affected the islands, indicating that viable corals may be available for some time after an incident, although this depends on subsequent wave energy. However, to maximize the likelihood of survival, corals should be reattached as soon as possible after they are detached from the substrate. Fragments or loose colonies may have been washed away from the reef site by wave energy and land in unsuitable habitat for survival and growth. Thus, some sites could benefit from replanting the reef with propagated corals from nurseries to restore or enhance the coastal protection services provided by nearshore coral reefs.

Recommendations for future response efforts

Most of the assessment and stabilization activities took place approximately 6 months or more after the impacts of the hurricanes. In the immediate aftermath of a major hurricane, protection of human life and property is a priority. Once a science response is feasible and realistic within the context of local conditions, additional limiting factors include logistics, safety, and staffing. Logistics and safety limitations can include medical and safety capacity, electricity, internet availability, food and lodging options, vessel, crew, and scientist availability, and field gear acquisitions (e.g., clipboards, tank fills). Local knowledge of resources, geography, and reefs was critical to success. Local teams were supported by a network of experts who were located in geographies unaffected by the hurricanes. A rapid large-scale response may be enabled by infrastructure and plans developed and identified in advance, such as a hurricane response plan and an updated list of response capacity both in the geographic region and outside of the region.

This effort took a diverse team with varying expertise and local knowledge to be successful. Continuous communications between the assessment and restoration teams were key to allow for flexibility and adaptation as needed to changing terrestrial and marine conditions post-hurricane. Regular, efficient communication and data coordination between field and shoreside teams were essential to the entire process, and specifically to efficient selection and prioritization of stabilization sites. As near-real-time data entry as possible was key to allow for adaptations and mid-course corrections as needed for both the assessment and stabilization efforts.

The assessment survey was designed within the framework of regular ecosystem monitoring to the extent possible. This maximized the use of existing scientific infrastructure (e.g., code, databases, data structure and organization) and potential comparisons between assessment and ecosystem monitoring datasets. Large-scale remote sensing efforts were considered for the assessment methodology, but were not included due to: 1) the time required for processing and analyses, 2) the need for assessment data to be quickly available to inform the stabilization team's rapid response efforts, 3) the processing and analysis time required for large-scale remote sensing, and 4) logistical limitations post-storm. Quantitative information on coral stabilization efforts was also important to include for both accurate representation of restoration efforts and subsequent monitoring to evaluate success. The development of a plan for quantitative data collection for both damage assessment and emergency coral stabilization facilitates achieving project goals and the methods described herein can serve as an example for guiding future efforts.

Force Blue

REFERENCES

Alvarez-Filip, L., Dulvy, N. K., Gill, J. A., Cote, I. M., & Watkinson, A. R. (2009). Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proceedings of the Royal Society B: Biological Sciences, 276*(1669), 3019-3025. doi:10.1098/rspb.2009.0339

Cangialosi, J. P., Latto, A. S., & Berg, R. (2018). National Hurricane Center Tropical Cyclone Report: Hurricane Irma. National Oceanic and Atmospheric Administration, National Weather Service Report (AL112017), 111 pp.

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications, 5*(3794).

Griffin, S. P., Nemeth, M. I., Moore, T. D., & Gintert, B. (2015). Restoration using *Acropora cervicornis* at the T/V MARGARA grounding site. *Coral Reefs, 34*(855).

Harmelin-Vivien, M. L. (1994). The effects of storms and cyclones on coral reefs: a review. *Journal of Coastal Research, 12SI*, 211-231.

Jensen, J. R. (2005). Introductory Digital Image Processing, A Remote Sensing Perspective (3rd ed.). Prentice- Hall, Inc., Saddle River, New Jersey, 526pp.

Kågesten, G., Sautter, W., Edwards, K., Costa, B., Kracker, L., & Battista, T. (2015). *Shallow-water benthic habitats of Northeast Puerto Rico and Culebra Island*. Retrieved from Silver Spring, MD: https://coastalscience.noaa.gov/project/benthic-habitat-mapping-northeast-puerto-rico-culebra/

Kendall, M. S., Monaco, M. E., Buja, K. R., Christensen, J. D., Kruer, C. R., Finkbeiner, M., & Warner, R. A. (2001). *Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands* Retrieved from Silver Spring, MD: https://coastalscience.noaa.gov/project/benthic-habitat-mapping-puerto-rico-virgin-islands/

Lirman, D. (2000). Fragmentation in the branching coral *Acropora palmata* (Lamarck): growth, survivorship, and reproduction of colonies and fragments. *Journal of Experimental Marine Biology and Ecology, 241*, 41-57.

McLeod, I. M., Williamson, D. H., Taylor, S., Srinivasan, M., Read, M., Boxer, C., Mattocks, N., & Ceccarelli, D. M. (2019). Bommies away! Logistics and early effects of repositioning 400 tonnes of displaced coral colonies following cyclone impacts on the Great Barrier Reef. *Ecological Management & Restoration, 20*(3), 262-265.

Meadows, D. & Bosnan, D. (2008). Lessons for minimizing impacts to coral reef and other ecosystems from the 2004 tsunami. *American Fisheries Society Symposium, 64*.

NMFS (2006). Endangered and Threatened Species: Final Listing Determinations for Elkhorn and Staghorn Coral. 50 CFR 223.

NMFS (2014). Endangered and Threatened Wildlife and Plants: Final Listing Determinations on Proposal to List 66 Reef-Building Coral Species and To Reclassify Elkhorn and Staghorn Corals, 50 CFR 223.

Pasch, R. J., Penny, A. B., & Berg, R. (2019). National Hurricane Center Tropical Cyclone Report: Hurricane Maria. National Oceanic and Atmospheric Administration, National Weather Service Report (AL152017), 48 pp.

Spalding, M. D., McIvor, A. L., Beck, M. W., Koch, E. W., Müller, I., Reed, D. J., Rubinoff, P., Spencer, T., Tolhurst, T.J., Wamsley, T.V., van Wesenbeeck, B.K., Wolanski, E., & Woodroffe, C. D. (2014). Coastal ecosystems: a critical element of risk reduction. *Conservation Letters, 7*(3), 293-301.

Stoddart, D. R. (1962). Catastrophic storm effects on the British Honduras reefs and cays. *Nature, 196*(4854), 512-515. doi:10.1038/196512a0

Storlazzi, C.D., Reguero, B.G., Cole, A.D., Lowe, E., Shope, J.B., Gibbs, A.E., Nickel, B.A., McCall, R.T., van Dongeren, A.R., & Beck, M.W. (2019). Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction: U.S. Geological Survey Open-File Report 2019–1027, 42 p. https://doi.org/10.3133/ofr2019

Viehman, S., Buckel, C., Griffin, S., Groves, S., Nemeth, M., Moore, J., Moore, T. (2020). NCCOS Assessment: Assessment of Puerto Rico’s coral reefs following Hurricanes Irma and Maria from 2017-09-16 to 2018-07-02 (NCEI Accession 022189). NOAA National Centers for Environmental Information. https://accession.nodc.noaa.gov/0221189

APPENDICES

Appendix A: Datasheet for transect assessment surveys

NAME/ BUDDY	**DATE**	**Transect Width _____(m) Length ______(m)**
SITE CODE	**TIME**	**HB in Transect (%) ________ in Cell (%) ________**
LAT/LON PHOTO VID	**Transect # ________of ______/ site**	**Hab Type _______ Transect (%)____Cell (%)____**
TRANSECT HEADING VIZ(m)	**Survey depth (ft)**	**Est. of loose corals in 50x50m cell #_________**
Stabilization Site Potential: High Medium Low No damage	**% rubble at site**	**Est. # loose corals in other area (# | area) #_______ _______m2**
Restoration Site Potential: High Medium Low No damage		**Damage to site: Severe Moderate Minor None** **Damage to: Corals Framework Both**

SPECIES CODE	CORAL TYPE I = Attached-Unbroken; B = Attached-Broken; U = Upside down/ Overturned/ Loose; LF = Loose frag AF = Attached frag	CORAL HEALTH D = Disease; BL = Bleached; O = Dead (F only)	# MEDIUM 20-50cm	# LARGE 51-100cm	# XL 101-150cm	THICKET (T) or # GIANT >150cm

SPP: ACR CERV, ACR PALM, ACR PROL, DEN CYLI, COL NATA, DIP LABY, MON CAVE, ORB ANNU, ORB FAVE, ORB FRAN, branching POR SPP., PSE STRI

Thicket codes: [L = est. max length (cm); W = est. max width (cm); % = est. % of thicket damaged (%)]

Habitat type codes: AGRF = Aggregated reef (linear), PTCH = Patch reef, BDRK = Bedrock, PVMT = Pavement

Damage codes: **SEVERE** = > 50% damage to corals & reef **MODERATE** = 10% - 50% damage to corals & reef **MINOR** = < 10% damage to corals & reef

Stabilization codes: HIGH = > 300 corals to be reattached (> 20 cm); many ESA species impacted **MED** = > 100 corals to be reattached (> 20 cm); some ESA species impacted **LOW** = < 100 corals to be reattached

Restoration sites codes: HIGH = signif damage, restoration reqd for recovery, needs additional assessment **MED** = moderate damage, might require restoration, possibly additional assessment **LOW** = damage present but natural recovery likely

Appendix B: Datasheet for roving diver assessment surveys

NAME/ BUDDY	ASSESS NEARBY (Y/N)	GPS TRACK RECORDED Y N
DATE	ASSESS SITE CODE	GPS START TIME END TIME
TIME	Survey # ________of _______/ site	TRACK WIDTH VIZ(m)
PHOTO VIDEO	Avg depth (ft)	HB in survey (%) _________
Stabilization Site Potential: High Medium Low No damage	% rubble in survey	Hab Type ________ (%)____
Recovery Site Potential: High Medium Low No damage		Damage to site: Severe Moderate Minor None Damage to: Corals Framework Both

SPECIES CODE	NO BREAKAGE	CORAL TYPE B = Attached-Broken; U = Upside down/ Overturned/ Loose; AF = Attached frag LF = Loose frag	# MEDIUM 20-50cm	# LARGE 51-100cm all spp	# XL 101-150cm all spp	# GIANT >150cm all spp

TIME/OBS (P = PIC)
SPP: ACR CERV, ACR PALM, ACR PROL, DEN CYLI, COL NATA, DIP LABY, MON CAVE, ORB ANNU, ORB FAVE, ORB FRAN, branching POR SPP., PSE STRI
Damage codes: **SEVERE** = > 50% damage to corals & reef **MODERATE** = 10% - 50% damage to corals & reef **MINOR** = < 10% damage to corals & reef
Stabilization codes: HIGH = > 300 corals to be reattached (> 20 cm); many ESA species impacted **MED** = > 100 corals to be reattached (> 20 cm); some ESA species impacted **LOW** = < 100 corals to be reattached
Restoration sites codes: HIGA25:J30H = signif damage, restoration reqd for recovery, needs additional assessment MED = moderate damage, might require restoration, possibly additional assessment LOW = damage present but natural recovery likely

Appendix C: Datasheet for coral reattachment surveys

NAME	**DATE**	**Est. # of At-Risk and Reattached Corals**			
SITE	**DEPTH (ft)**	Initial #	# Reattached	# Remaining	% Complete
LAT	**Area Covered (m2):**				
LON	**Area Remaining (m2):**	**Day # for stabilization at site**			
Additional Stabilization Potential: High Medium Low No		**Est. # of days remaining:**			

Restoration Site Potential: High Medium Low No	**Damage to site:** Severe Moderate Minor None

SPECIES CODE	# SMALL < 20cm	# MEDIUM 20-50cm	# LARGE 51-100cm	# XL 101-150cm	# GIANT >150cm	THICKET branching spp

SPP: ACR CERV, ACR PALM, DEN CYL, COL NAT, DIP LAB, MON CAV, ORB ANN, ORB FAV, ORB FRA, branching POR SPP., PSE STR

Description of Remaining Work:

Appendix D: Assessment survey locations

Table D.1. Assessment survey site names, locations, and survey areas for both transect and roving surveys.

Site Name	Latitude	Longitude	Transect area (m^2)	Roving area (m^2)
Dominoes 1	18.46081	-66.0529	NA	8307
Dominoes 2	18.46215	-66.0514	NA	6601
N_037	18.51418	-67.1043	500	2095
N_040	18.5155	-67.101	500	2224
N_048	18.45132	-65.9552	500	1846
N_053	18.45547	-66.0464	500	1810
N_054	18.45627	-66.0402	500	1766
N_055	18.45611	-66.0244	500	1584
N_069	18.46048	-66.0496	500	1788
N_076	18.46355	-65.9862	500	3240
N_089	18.46961	-66.1143	500	3526
N_093	18.47084	-66.1067	500	2153
N_094	18.47198	-66.1521	500	1871
N_095	18.47248	-66.1549	500	1919
N_099	18.47694	-66.3053	500	NA
N_101	18.47665	-66.1922	500	NA
N_104	18.47953	-66.3007	500	NA
N_113	18.4857	-66.3501	500	3334
N_118	18.49109	-66.4139	500	2036
N_119	18.49276	-66.4005	500	2555
N_120	18.49368	-66.4017	500	2152
NE_001	18.2341	-65.5509	500	2119
NE_002	18.2362	-65.5173	500	2393
NE_004	18.2781	-65.2747	500	2496

Table D.1. Continued. Assessment survey site names, locations, and survey areas for both transect and roving surveys.

Site Name	Latitude	Longitude	Transect area (m^2)	Roving area (m^2)
NE_005	18.2798	-65.2718	500	3753
NE_006	18.2803	-65.2486	1000	2109
NE_007	18.2852	-65.2438	500	3610
NE_016	18.2947	-65.2705	500	4098
NE_017	18.2972	-65.3035	500	3507
NE_018	18.2994	-65.3276	500	5599
NE_019	18.3005	-65.311	500	2439
NE_021	18.3032	-65.3379	500	3210
NE_022	18.302	-65.2302	500	2623
NE_025	18.3074	-65.2259	600	4974
NE_026	18.3083	-65.2287	500	3827
NE_027	18.3092	-65.2296	750	6718
NE_028	18.3122	-65.3358	500	3334
NE_029	18.3101	-65.2263	500	4489
NE_030	18.31325	-65.3331	500	5480
NE_031	18.315	-65.2224	500	3252
NE_039	18.3307	-65.3331	500	3536
NE_040	18.3317	-65.2485	500	3147
NE_041	18.333	-65.2461	500	3117
NE_050	18.3373	-65.2328	500	4746
NE_058	18.37111	-65.6555	500	4396
NE_067	18.3763	-65.6544	500	2259
NE_069	18.37647	-65.6391	500	2311
NE_070	18.3753	-65.5708	500	2266
NE_072	18.37834	-65.6386	500	2394
NE_073	18.3797	-65.6454	500	2483

Table D.1. Continued. Assessment survey site names, locations, and survey areas for both transect and roving surveys.

Site Name	Latitude	Longitude	Transect area (m^2)	Roving area (m^2)
NE_075	18.38216	-65.7361	500	1321
NE_077	18.3793	-65.5726	500	2796
NE_078	18.3805	-65.5853	500	3934
NE_082	18.384	-65.5786	500	4253
NE_090	18.39296	-65.7248	500	1961
NE_091	18.39346	-65.7271	500	3007
NE_092	18.3909	-65.5861	500	3604
NE_093	18.3944	-65.7325	500	2435
NE_094	18.3923	-65.5908	500	3682
NE_457	18.3132	-65.5805	1000	NA
NE_465	18.3212	-65.5789	1000	NA
NE_471	18.3373	-65.5654	500	NA
NE_476	18.3428	-65.5728	500	NA
NE_480	18.3494	-65.5642	500	NA
NE_483	18.3545	-65.5717	1000	NA
NE_502	18.28427	-65.2443	500	3837
NE_505	18.30454	-65.3119	500	2306
NE_511	18.28005	-65.2822	500	4351
NE_515	18.29715	-65.3031	500	2054
NE_517	18.30078	-65.3276	500	2873
NE_524	18.30593	-65.3375	500	2645
NE_525	18.30684	-65.3378	500	3218
NE_526	18.30916	-65.3175	500	2042
NE_531	18.32265	-65.326	500	2580
NE_535	18.376	-65.5793	500	4518
NE_536	18.30909	-65.5801	500	3626

Table D.1. Continued. Assessment survey site names, locations, and survey areas for both transect and roving surveys.

Site Name	Latitude	Longitude	Transect area (m^2)	Roving area (m^2)
NE_537	18.31402	-65.5786	500	3615
NE_538	18.32919	-65.6194	500	2651
NE_539	18.33279	-65.6197	500	3029
NE_545	18.37996	-65.5816	500	3287
NE_547	18.39097	-65.587	500	3106
Rompeolas	18.43599	-67.1571	NA	10751
SE_002	17.91228	-66.2229	500	1315
SE_004	17.91585	-66.2196	500	424
SE_007	17.92688	-66.1397	500	NA
SE_016	17.94958	-66.0879	500	NA
SE_017	17.96628	-66.0282	400	724
SE_022	17.98776	-65.8727	500	1607
SE_024	17.98817	-65.8698	500	2653
SE_033	18.05372	-65.8205	100	588
SE_040	18.15563	-65.7077	500	1134
SE_507	17.91581	-66.2172	500	NA
SE_514	17.93217	-66.2841	300	1697
SE_518	17.94035	-66.1041	500	NA
SE_540	18.03833	-65.8185	500	2546
SE_542	18.0398	-65.825	100	221
SE_543	18.04109	-65.8212	300	1181
SW_002	17.88216	-66.5347	500	496
SW_009	17.90172	-66.5103	500	3343
SW_010	17.91467	-66.4984	500	4550
SW_011	17.91915	-66.461	500	2833
SW_015	17.92889	-67.1196	500	1883

Table D.1. Continued. Assessment survey site names, locations, and survey areas for both transect and roving surveys.

Site Name	Latitude	Longitude	Transect area (m^2)	Roving area (m^2)
SW_016	17.92774	-67.004	500	2266
SW_017	17.92958	-66.9204	500	1586
SW_018	17.93339	-67.1172	500	1696
SW_019	17.93534	-67.0186	500	1642
SW_020	17.9427	-66.9226	500	930
SW_023	17.94978	-66.9089	500	991
SW_024	17.95023	-66.9089	500	701
SW_027	17.96991	-66.7307	500	686
SW_030	17.973	-66.7524	500	867
SW_512	17.89559	-66.5251	500	2963
SW_526	17.96661	-66.7581	500	2371
VQ_001	18.08291	-65.5496	500	4792
VQ_002	18.08178	-65.4869	500	2290
VQ_003	18.08338	-65.5506	500	5186
VQ_004	18.08228	-65.4897	500	3382
VQ_005	18.08397	-65.5586	500	2916
VQ_007	18.08489	-65.5595	500	21078
VQ_008	18.08748	-65.5619	500	4374
VQ_011	18.08765	-65.4662	500	1107
VQ_013	18.08842	-65.4743	500	5618
VQ_015	18.08823	-65.4452	500	3438
VQ_019	18.09187	-65.5711	500	3646
VQ_024	18.10099	-65.5766	500	3016
VQ_026	18.147	-65.4479	500	519
VQ_028	18.15618	-65.509	500	1320
VQ_029	18.15727	-65.4698	500	441

Table D.1. Continued. Assessment survey site names, locations, and survey areas for both transect and roving surveys.

Site Name	Latitude	Longitude	Transect area (m^2)	Roving area (m^2)
VQ_034	18.16133	-65.4943	500	2242
VQ_035	18.16185	-65.4991	500	3582
VQ_037	18.16059	-65.4296	500	762
VQ_038	18.16278	-65.4994	500	3425
VQ_039	18.16244	-65.4856	500	898
W_005	18.48228	-67.1676	500	2427
W_009	18.01963	-67.2083	500	3370
W_010	18.04459	-67.2029	500	4251
W_011	18.06003	-67.2792	500	2413
W_015	18.11637	-67.2645	500	4468
W_019	18.15094	-67.2415	500	1997
W_021	18.18291	-67.2298	500	2526
W_023	18.1907	-67.1886	500	3071
W_024	18.19383	-67.19	500	2842
W_029	18.34452	-67.2621	500	1416
W_502	18.35993	-67.272	500	1987
W_503	18.36128	-67.2715	500	3528
W_024	18.19383	-67.19	500	2842
W_029	18.34452	-67.2621	500	1416
W_502	18.35993	-67.272	500	1987
W_503	18.36128	-67.2715	500	3528
W_505	18.3658	-67.2715	500	3040
W_510	18.47416	-67.1696	500	2398
W_517	18.01635	-67.2447	500	3409
W_527	18.34311	-67.261	500	1205
W_529	18.3463	-67.2632	500	1806

Appendix E: Summary information for coral species in transect assessment surveys

Table E.1 Number of damaged colonies, total number of colonies, damage prevalence (%), and number of fragments (Fr) for each species from transect assessment surveys.

Species name	Species code	Damaged colonies	Total colonies	Damage (%)	Fr
Acropora palmata	ACR PALM	190	421	45.1	994
Acropora cervicornis	ACR CERV	62	165	37.6	151
Acropora prolifera	ACR PROL	26	73	35.6	46
Dendrogyra cylindrus	DEN CYLI	90	117	76.9	14
Orbicella annularis	ORB ANNU	659	1548	42.6	1
Colpophyllia natans	COL NATA	14	118	11.9	0
Pseudodiploria clivosa	DIP CLIV	39	2784	1.4	0
Diploria labyrinthiformis	DIP LABY	49	339	14.5	0
Montastrea cavernosa	MON CAVE	73	1983	3.7	0
Orbicella faveolata	ORB FAVE	139	1166	11.9	0
Orbicella franksi	ORB FRAN	49	494	9.9	0
Porites astreoides	POR ASTE	169	5936	2.8	0
Branching *Porites* species	BR POR SPP	445	942	47.2	174
Pseudodiploria strigosa	PSE STRI	656	7309	9.0	0
Siderastrea siderea	SID SIDE	266	3558	7.5	0

Table E.2 Mean density and standard error (SE) of coral damage (per 50 m^2) by species and number of sites where damaged species were present (n) from transect assessment surveys.

Species name	Species code	Density	SE	n
Acropora cervicornis	ACR CERV	2.0	0.76	10
Acropora palmata	ACR PALM	4.3	1.4	35
Acropora prolifera	ACR PROL	1.9	0.66	3
Branching *Porites* species	BR POR SPP	12.4	3.5	32
Colpophyllia natans	COL NATA	1.2	0.05	9
Dendrogyra cylindrus	DEN CYLI	2.2	1.0	18
Diploria labyrinthiformis	DIP LABY	1.3	0.2	23
Montastrea cavernosa	MON CAVE	1.9	0.3	24
Orbicella annularis	ORB ANNU	5.9	1.2	41
Orbicella faveolata	ORB FAVE	2.5	0.5	40
Orbicella franksi	ORB FRAN	1.8	0.3	23
Porites astreoides	POR ASTE	5.0	0.9	45
Pseudodiploria clivosa	DIP CLIV	1.3	0.3	17
Pseudodiploria strigosa	PSE STRI	6.19	0.9	97
Siderastrea siderea	SID SIDE	5.0	1.1	55

Appendix F: Summary information for coral species in roving assessment surveys

Table F.1 Number of damaged colonies, total number of colonies, damage prevalence (%), and number of fragments (Fr) for each species from roving assessment surveys.

Species name	Species code	Damaged colonies	Total colonies	Damage (%)	Fr
Acropora cervicornis	ACR CERV	65	120	54.2	713
Acropora palmata	ACR PALM	1445	1885	76.7	3967
Acropora prolifera	ACR PROL	30	84	35.7	215
Branching *Porites* species	BR POR SPP	633	1515	41.8	305
Colpophyllia natans	COL NATA	23	236	9.7	0
Dendrogyra cylindrus	DEN CYLI	102	222	45.9	30
Diploria labyrinthiformis	DIP LABY	169	801	21.1	0
Montastrea cavernosa	MON CAVE	145	2535	5.7	0
Orbicella annularis	ORB ANNU	1231	2824	43.6	4
Orbicella faveolata	ORB FAVE	334	2381	14.0	0
Orbicella franksi	ORB FRAN	127	933	13.6	0
Porites astreoides	POR ASTE	325	8776	3.7	0
Pseudodiploria clivosa	DIP CLIV	76	4889	1.6	0
Pseudodiploria strigosa	PSE STRI	2186	17979	12.2	0
Siderastrea siderea	SID SIDE	511	7123	7.2	0

Table F.2 Mean density and standard error (SE) of coral damage (per 100 m^2) by species and number of sites where damaged species were present (n) from roving assessment surveys.

Species name	Species code	Density	SE	n
Acropora cervicornis	ACR CERV	0.3	0.1	9
Acropora palmata	ACR PALM	3.8	3.0	58
Acropora prolifera	ACR PROL	0.2	NA	1
Branching *Porites* species	BR POR SPP	2.1	1.4	41
Colpophyllia natans	COL NATA	0.1	0.1	20
Dendrogyra cylindrus	DEN CYLI	0.2	0.1	31
Diploria labyrinthiformis	DIP LABY	0.3	0.1	34
Montastrea cavernosa	MON CAVE	0.3	0.1	39
Orbicella annularis	ORB ANNU	1.5	0.4	57
Orbicella faveolata	ORB FAVE	0.3	0.1	63
Orbicella franksi	ORB FRAN	0.2	0.1	30
Porites astreoides	POR ASTE	1.3	0.7	69
Pseudodiploria clivosa	PSE CLIV	1.2	1.1	22
Pseudodiploria strigosa	PSE STRI	5.8	3.8	113
Siderastrea siderea	SID SIDE	1.7	1.1	80

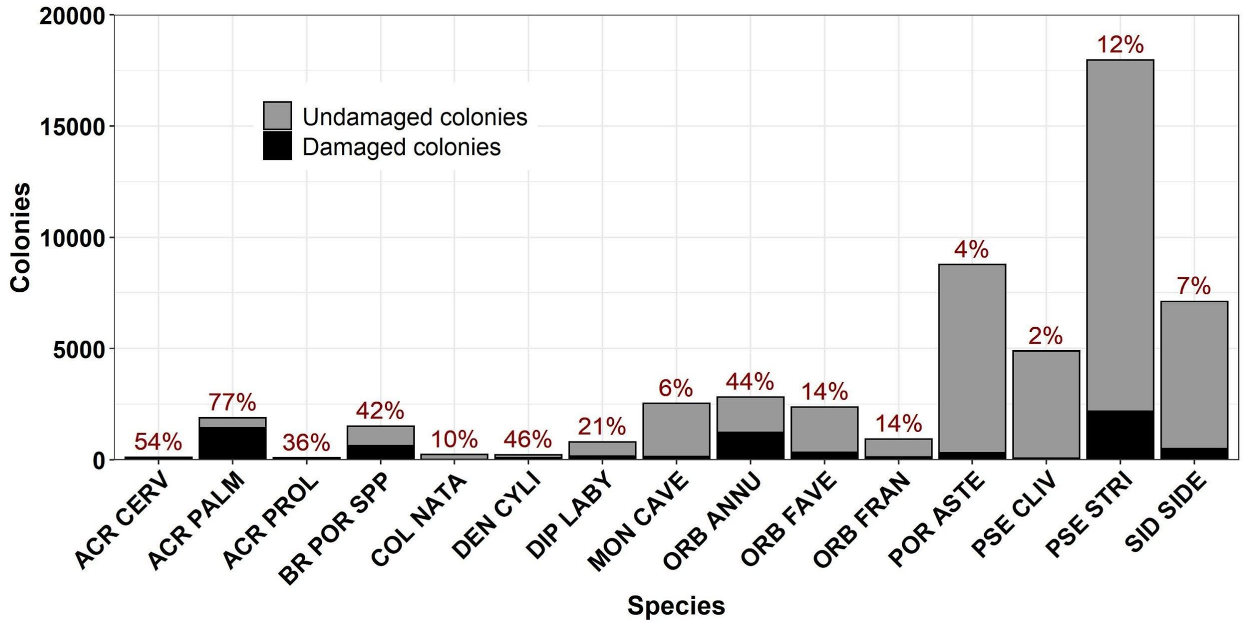


Figure F.1 Damage by coral species counted in roving assessment surveys. Red values indicate damage prevalence (percentage of total colonies with damage). Species names and abbreviations are in the Species Abbreviations.

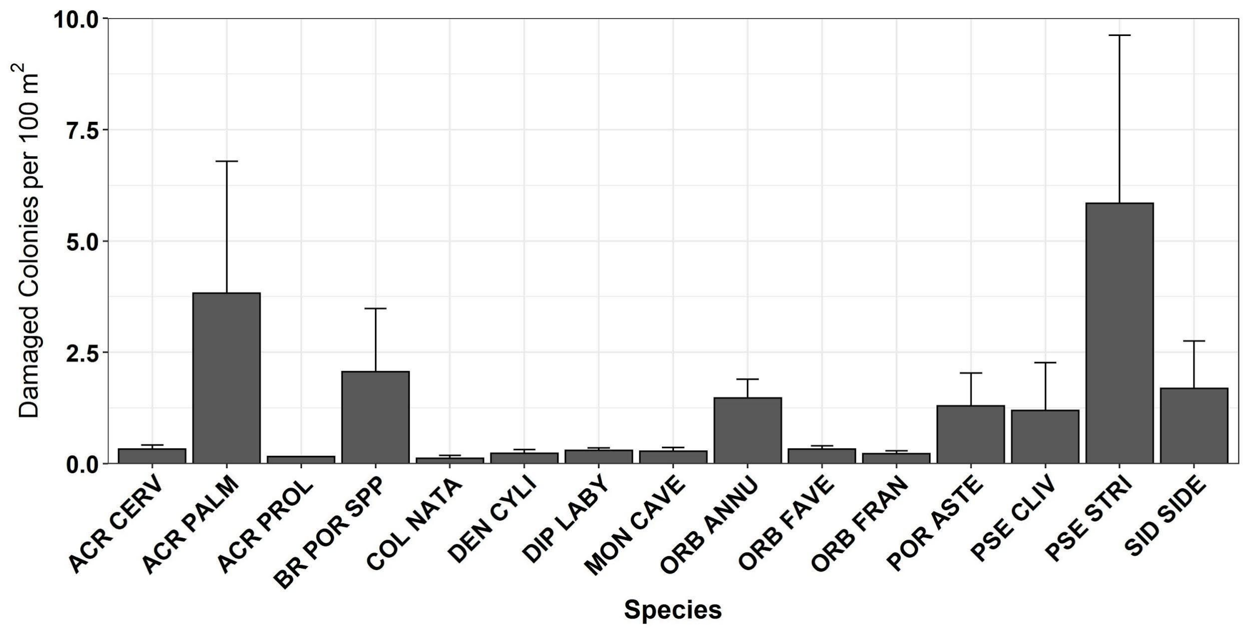


Figure F.2 Mean density (+/- standard error) of coral damage by species from roving assessment surveys. Species names and abbreviations are in the Species Abbreviations.

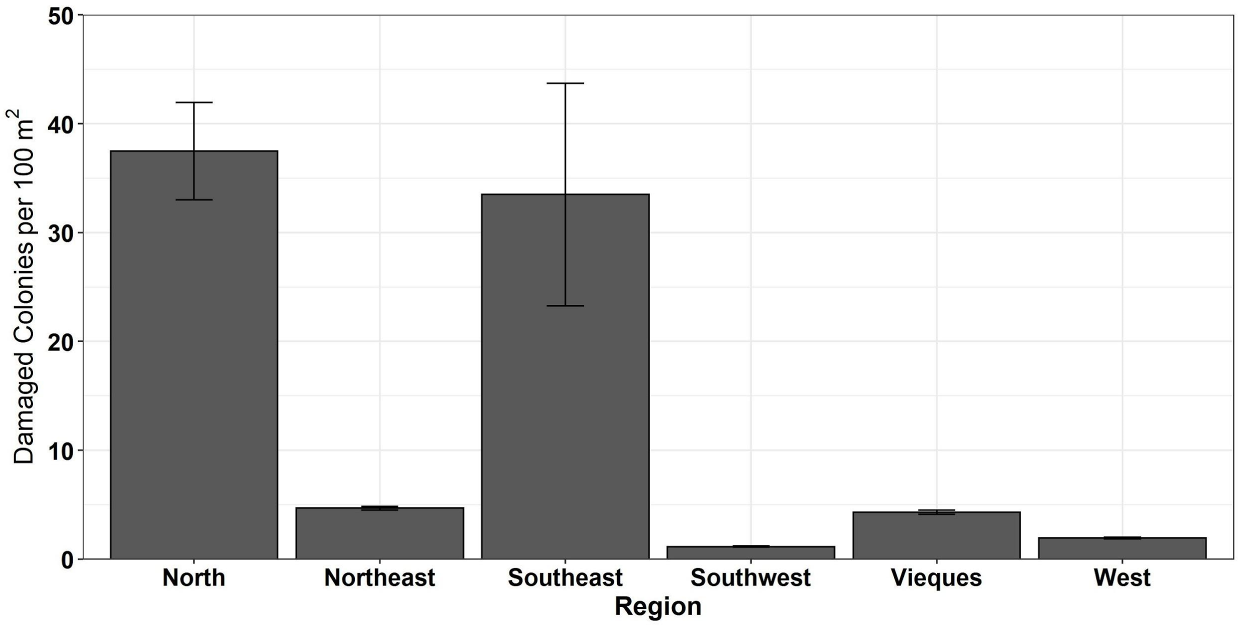


Figure F.3 Mean density (+/- standard error) of coral damage by region from roving assessment surveys.

Appendix G: Detailed information on the five surveyed sites with the most severe damage to *Acropora palmata* (elkhorn coral)

Summary figures are provided below for each of the five sites with the most severe damage to *A. palmata* (from Figure 15).

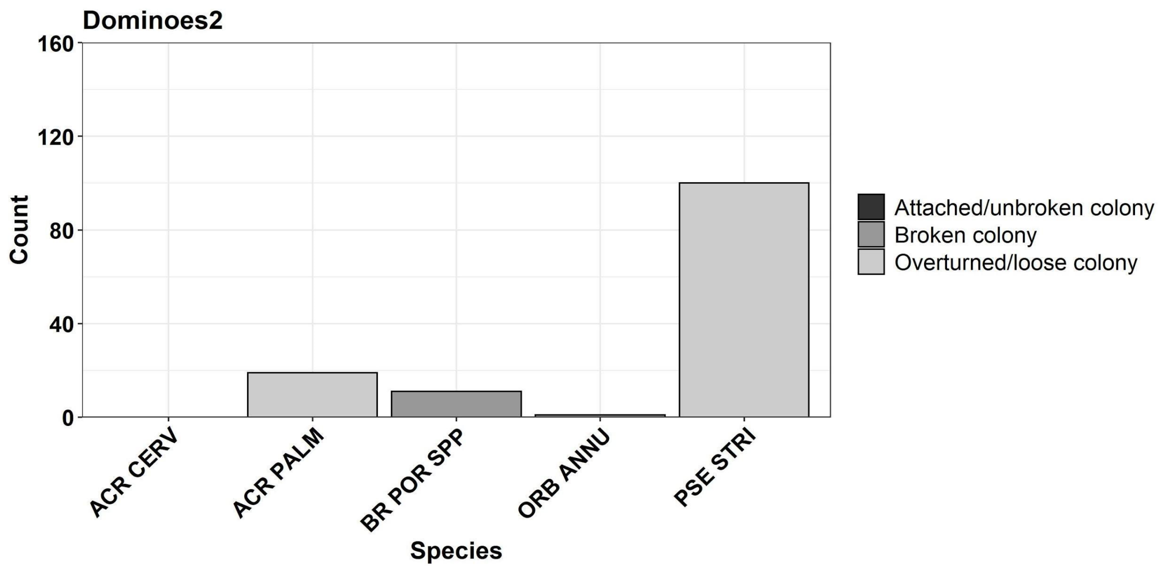


Figure G.1 Number of damaged and undamaged colonies for all species impacted at site Dominoes2. Species impacted included *Acropora cervicornis, A. palmata*, branching *Porites* species, *Orbicella annularis,* and *Pseudodiploria strigosa*.

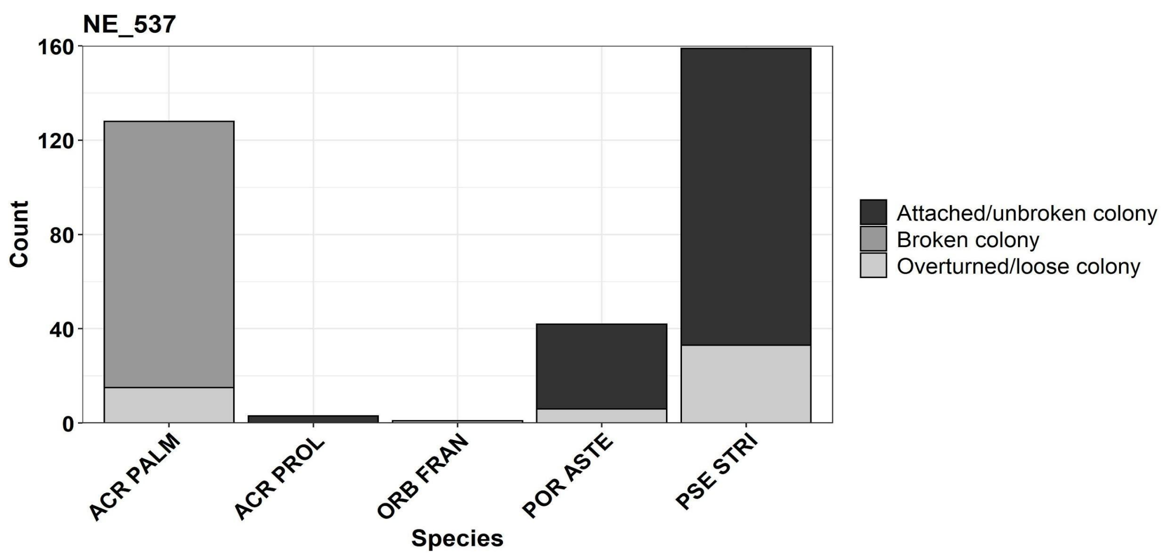


Figure G.2 Number of damaged and undamaged colonies for all species impacted at site NE_537. Damaged species included *Acropora palmata, A. prolifera, Orbicella franksi, Portites astreoides,* and *Pseudodiploria strigosa*.

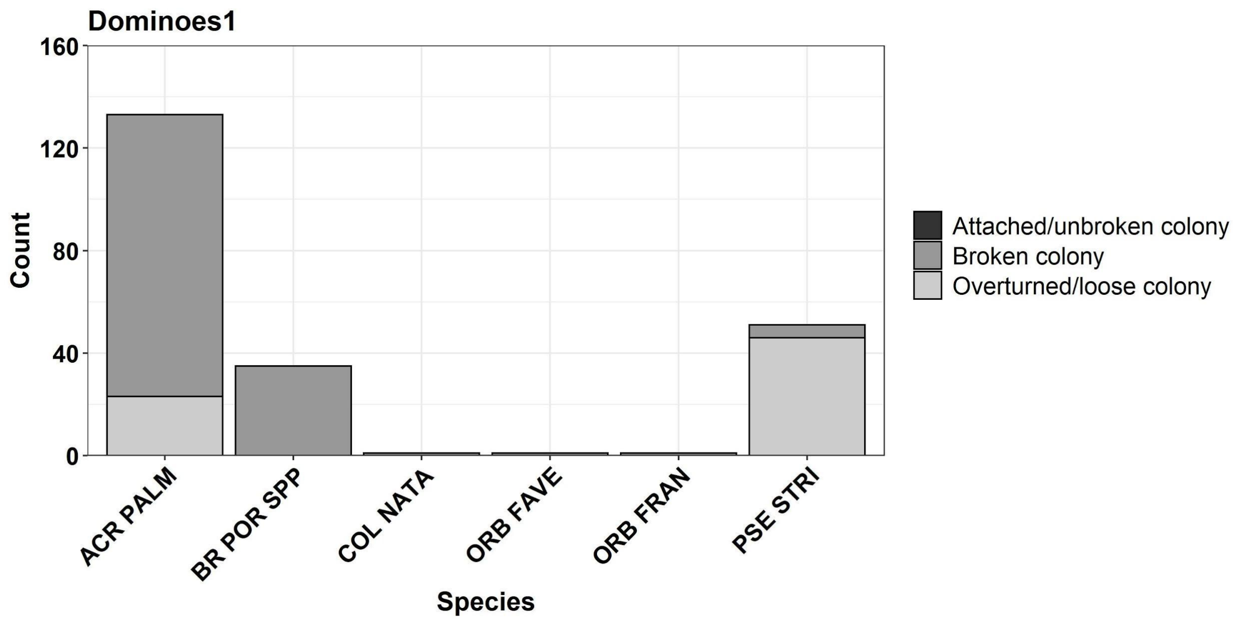


Figure G.3 Number of damaged and undamaged colonies for all species impacted at site Dominoes1. Damaged species included *Acropora palmata,* branching *Porites* species*, Colpophyllia natans, Orbicella faveolata, Orbicella franksi,* and *Pseudodiploria strigosa.*

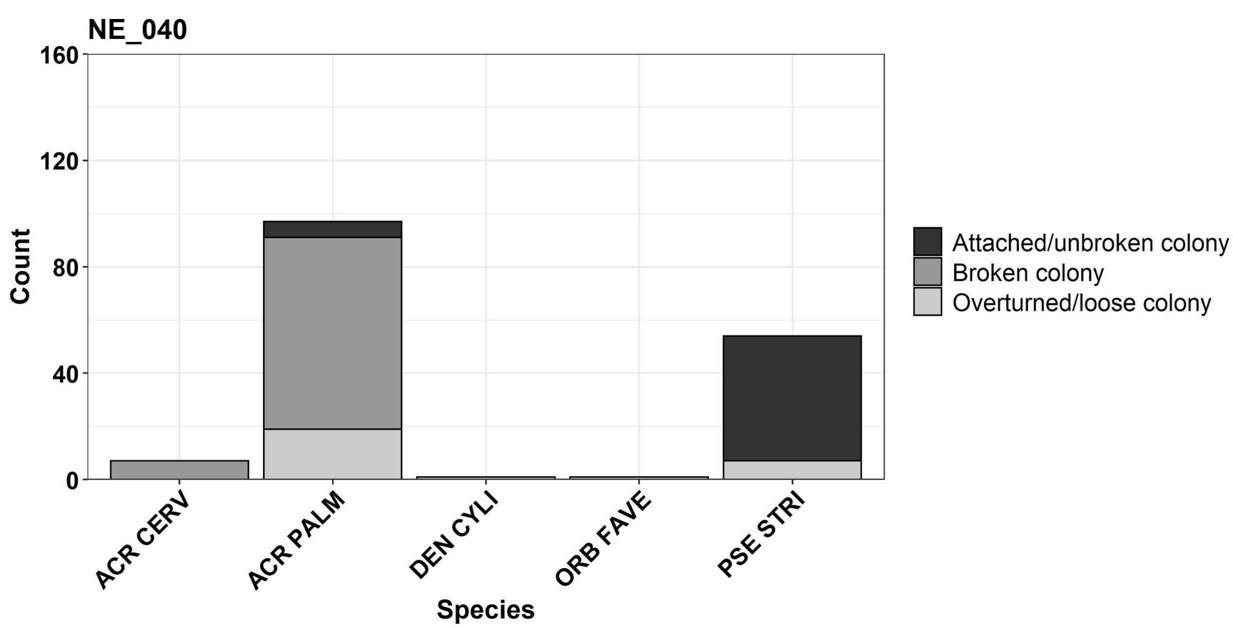


Figure G.4 Number of damaged and undamaged colonies for all species impacted at site NE_040. Damaged species included *Acropora cervicornis, A. palmata, Dendrogyra cylindrus, Orbicella faveolata,* and *Pseudodiploria strigosa.*

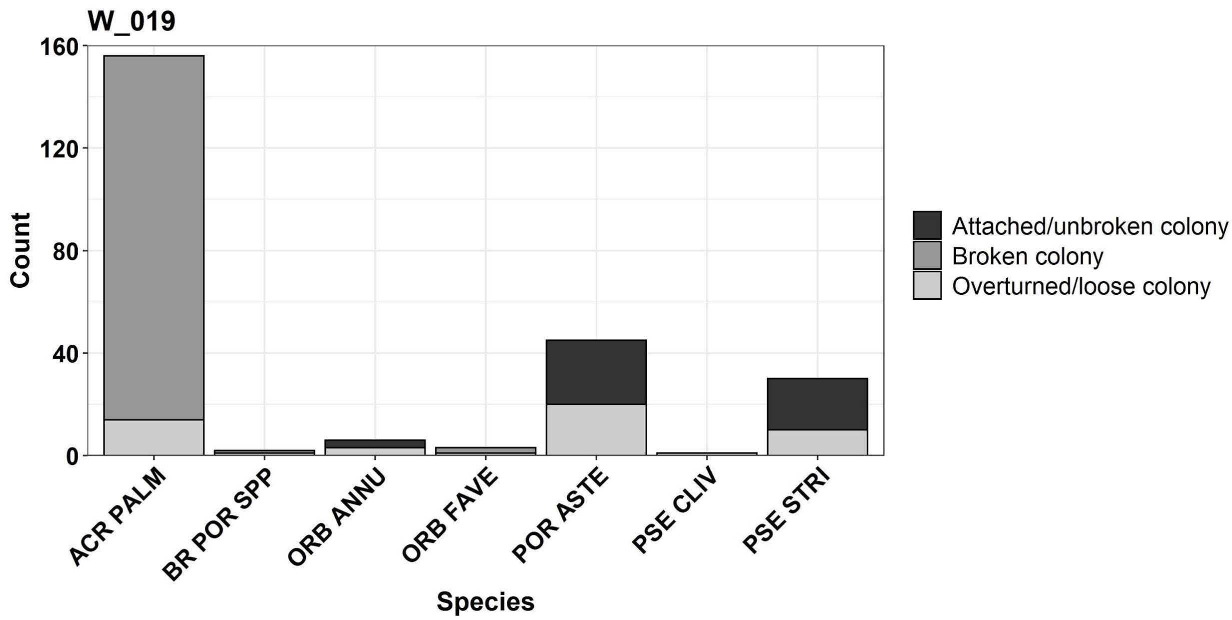


Figure G.5 Number of damaged and undamaged colonies for all species impacted at site W_019. Damaged species included *Acropora palmata,* branching *Porites* species*, Orbicella annularis, O. faveolata, Porites astreoides,* and *Pseudodiploria clivosa, P. strigosa.*

Appendix H: Detailed information on the five surveyed sites with the most severe damage to *Orbicella annularis* (lobed star coral)

Summary figures are provided below for each of the five sites with the most severe damage to *O. annularis* (from Figure 19).

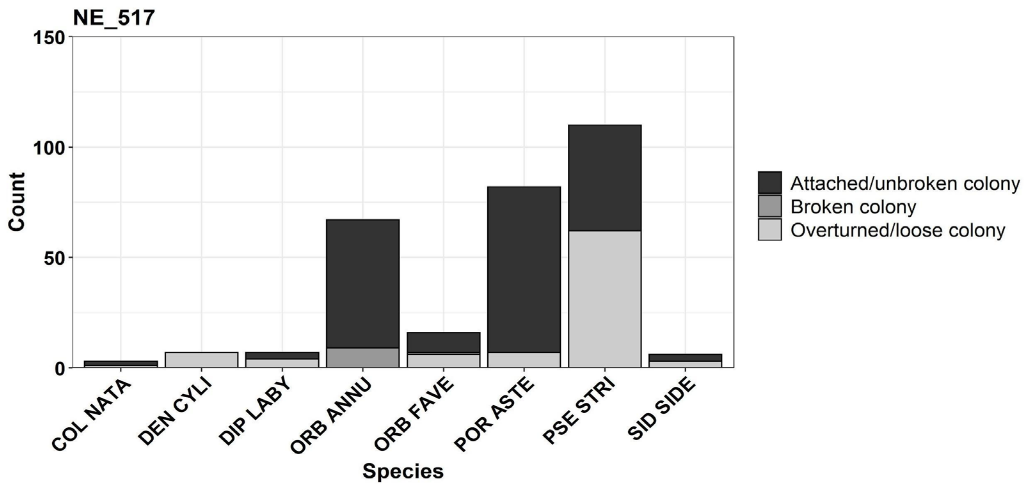


Figure H.1 Number of damaged and undamaged colonies for all species impacted at site NE_517. Damaged species included *Colpophyllia natans, Dendrogyra cylindrus, Diploria labyrinthiformis, Orbicella faveolata, Porites astreoides, Pseudodiploria strigosa,* and *Siderastrea siderea*.

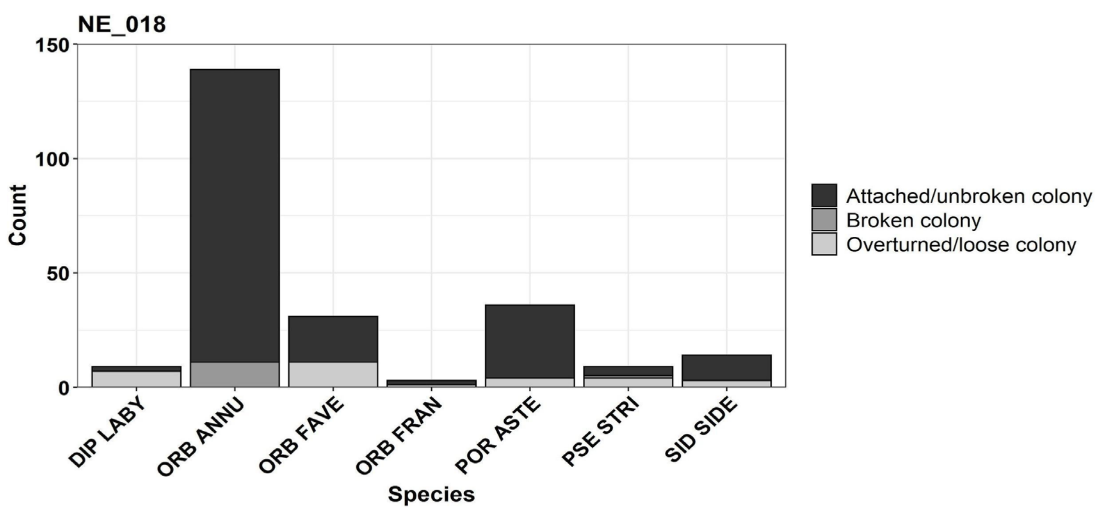


Figure H.2 Number of damaged and undamaged colonies for all species impacted at site NE_018. Damaged species included *Diploria labyrinthiformis, Orbicella annularis, O. faveolata, O. franksi, Porites astreoides, Pseudodiplora strigosa,* and *Siderastrea siderea*.

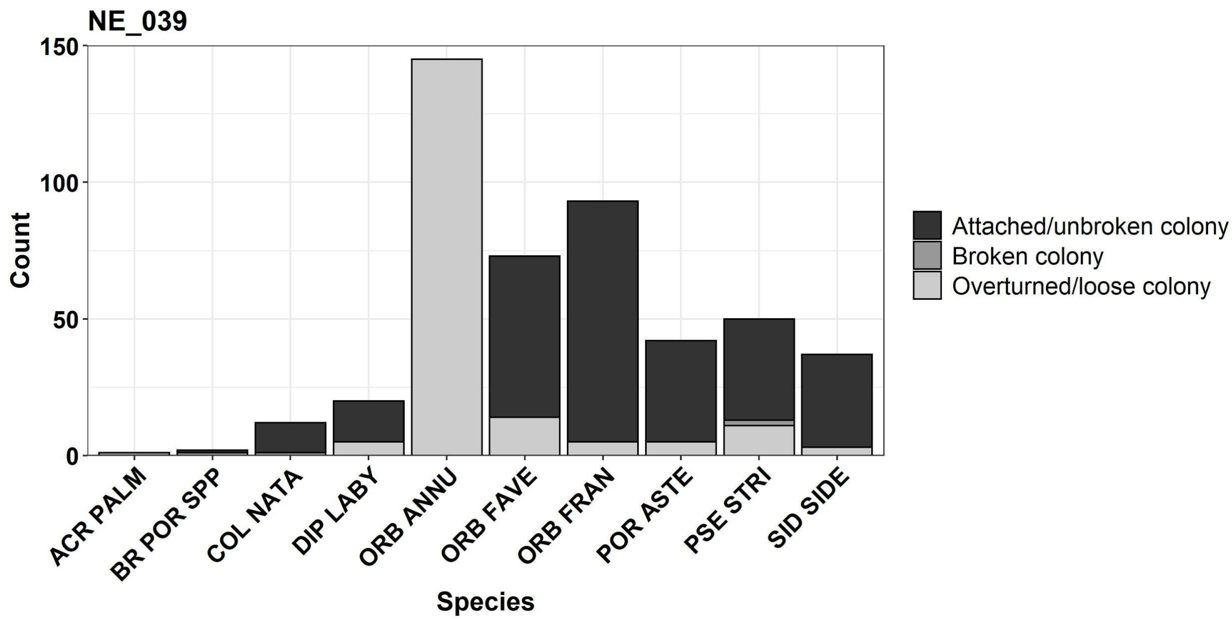


Figure H.3 Number of damaged and undamaged colonies for all species impacted at site NE_039. Damaged species included *Acropora palmata,* branching *Porites* species*, Colpophyllia natans, Diplora labyrinthiformis, Orbicella faveolata, O. franksi, Porites astreoides, Pseudodiplora strigosa,* and *Siderastrea siderea.*

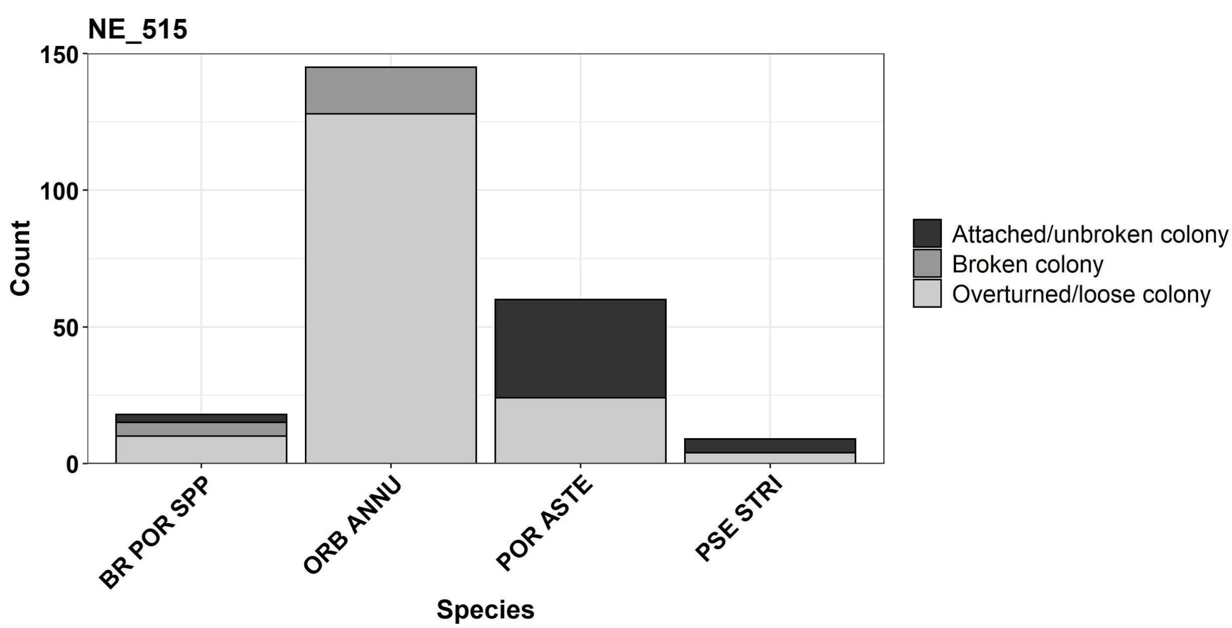


Figure H.4 Number of damaged and undamaged colonies for all species impacted at site NE_515. Damaged species included branching *Porites* species*, Orbicella annularis, Porites astreoides,* and *Pseudodiplora strigosa.*

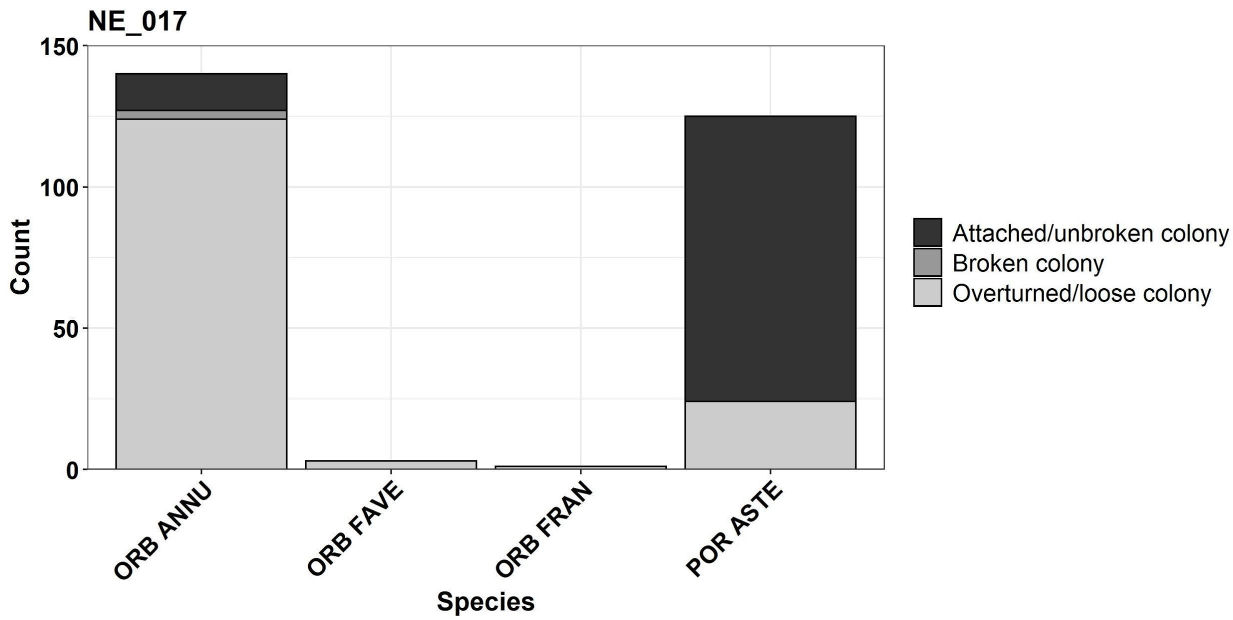


Figure H.5 Number of damaged and undamaged colonies for all species impacted at site NE_017. Damaged species included *Orbicella annularis, O. faveolata, O. franksi,* and *Porites astreoides.*

Appendix I: Coral stabilization site locations

Table I.1. Stabilization site name, effort name, territory, and location.

Site Name	Effort Name	U.S. Territory	Latitude	Longitude
Arrecife Mosquito	FEMA	Puerto Rico	18.16166	-65.4983
Bajo Merail 1	FEMA	Puerto Rico	18.14889	-65.4902
Bajo Merail 2	FEMA	Puerto Rico	18.14918	-65.4899
Carlos Rosario 1	FEMA	Puerto Rico	18.33066	-65.3331
Carlos Rosario 2	FEMA	Puerto Rico	18.32455	-65.3315
Carlos Rosario 3	FEMA	Puerto Rico	18.34575	-65.3413
Carlos Rosario 4	FEMA	Puerto Rico	18.33106	-65.3329
Cayo Diablo	FEMA	Puerto Rico	18.36068	-65.5309
Cayo Largo 1	FEMA	Puerto Rico	18.30833	-65.5774
Cayo Largo 2	FEMA	Puerto Rico	18.30553	-65.5786
Cayo Largo 3	FEMA	Puerto Rico	18.30945	-65.5778
Cayo Largo 4	FEMA	Puerto Rico	18.30618	-65.5789
Cayo Largo 5	FEMA	Puerto Rico	18.30662	-65.5795
Cayo Largo 6	FEMA	Puerto Rico	18.31403	-65.5791
Cayo Largo 7	FEMA	Puerto Rico	18.31447	-65.5792
Cayo Largo 8	FEMA	Puerto Rico	18.31472	-65.5794
Cayo Largo 9	FEMA	Puerto Rico	18.31531	-65.5797
Cueva del Indio	FEMA	Puerto Rico	18.4914	-66.6425
Dominoes 1	FEMA	Puerto Rico	18.46086	-66.0518
Dominoes 1	FEMA	Puerto Rico	18.46029	-66.053
Dominoes 1	FEMA	Puerto Rico	18.46167	-66.0513
Dominoes 2	FEMA	Puerto Rico	18.46029	-66.053
Dominoes 3	FEMA	Puerto Rico	18.46167	-66.0513
Isla Verde Reserve	FEMA	Puerto Rico	18.44962	-66.015
Los Corchos 1	FEMA	Puerto Rico	18.27982	-65.2493
Los Corchos 2	FEMA	Puerto Rico	18.27825	-65.2496

Table I.1. Continued… Stabilization site name, effort name, territory, and location.

Site Name	Effort Name	U.S. Territory	Latitude	Longitude
Los Corchos 3	FEMA	Puerto Rico	18.28042	-65.2492
Morcillas Nursery	FEMA	Puerto Rico	18.45969	-66.0395
Morcillas 1	FEMA	Puerto Rico	18.45905	-66.0372
Morcillas 2	FEMA	Puerto Rico	18.45923	-66.0383
Ocean Park Nursery	FEMA	Puerto Rico	18.46047	-66.0461
Penon de Mera	FEMA	Puerto Rico	18.48805	-66.6752
Punta Maguey 1	FEMA	Puerto Rico	18.29336	-65.3012
Vega Baja	FEMA	Puerto Rico	18.49226	-66.4088
VQ South Bank 1	FEMA	Puerto Rico	18.08228	-65.4897
VQ South Bank 2	FEMA	Puerto Rico	18.08134	-65.4873
Waimea	FEMA	Puerto Rico	18.46201	-66.0474
Buye	Pre-FEMA	Puerto Rico	18.03788	-67.2097
Corral	Pre-FEMA	Puerto Rico	17.94599	-67.0172
Diablo	Pre-FEMA	Puerto Rico	18.35988	-65.5323
Eco	Pre-FEMA	Puerto Rico	18.49226	-66.4088
Guanica	Pre-FEMA	Puerto Rico	17.9367	-66.8868
Lobos	Pre-FEMA	Puerto Rico	18.3746	-65.5684
Negro 1	Pre-FEMA	Puerto Rico	18.15284	-67.2423
Negro 2	Pre-FEMA	Puerto Rico	18.15294	-67.2437
Negro 3	Pre-FEMA	Puerto Rico	18.15113	-67.2442
Negro 4	Pre-FEMA	Puerto Rico	18.15274	-67.2438
Negro 5	Pre-FEMA	Puerto Rico	18.15001	-67.2432
Palominito	Pre-FEMA	Puerto Rico	18.33995	-65.5634
Palomino North	Pre-FEMA	Puerto Rico	18.35371	-65.5728
Ron 1	Pre-FEMA	Puerto Rico	18.0954	-67.2848
Ron 2	Pre-FEMA	Puerto Rico	18.0954	-67.2853
Ron 3	Pre-FEMA	Puerto Rico	18.10257	-67.2854
Shacks	Pre-FEMA	Puerto Rico	18.51601	-67.102

Table I.1. Continued… Stabilization site name, effort name, territory, and location.

Site Name	Effort Name	U.S. Territory	Latitude	Longitude
Tamarindo	Pre-FEMA	Puerto Rico	18.31464	-65.3183
Tamarindo Chico	Pre-FEMA	Puerto Rico	18.3117	-65.3164
Tractores	Pre-FEMA	Puerto Rico	18.49173	-66.4144
Tres Palmas	Pre-FEMA	Puerto Rico	18.35042	-67.2663
Tres Palmas	Pre-FEMA	Puerto Rico	18.35157	-67.2675
Brewers Bay	Pre-FEMA	US Virgin Islands	18.34366	-64.9856
Cow and Calf Rocks	Pre-FEMA	US Virgin Islands	18.30405	-64.8463
Flat Cay	Pre-FEMA	US Virgin Islands	18.31684	-64.9886
Great St. James	Pre-FEMA	US Virgin Islands	18.30343	-64.8361
Sapphire Bay	Pre-FEMA	US Virgin Islands	18.33249	-64.8465
Thatch Cay	Pre-FEMA	US Virgin Islands	18.35438	-64.8515
Perseverance	Pre-FEMA	US Virgin Islands	18.3471	-64.9983

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