Status of Puerto Rico's Coral Reefs in the Aftermath of Hurricanes Irma and Maria

Assessment Report Submitted by NOAA to the FEMA Natural and Cultural Resources Recovery Support Function

Executive Summary

In September 2017, Hurricanes Irma and Maria devastated the islands of Puerto Rico, including their extremely valuable coral reefs. In February 2018, the Federal Emergency Management Agency (FEMA) assigned the National Oceanic and Atmospheric Administration (NOAA) to conduct coral reef assessments and emergency triage restoration activities in support of the National Disaster Recovery Framework Natural and Cultural Resources Recovery Support Function. A total of 414,354 m^2 of coral reef and over 80,000 corals were surveyed at 153 sites across Puerto Rico between February 25 and May 7, 2018. Approximately, 5,400 coral fragments or broken coral colonies were reattached (triage) to the reef at 32 sites in the Northeast, North, and Vieques regions.

Overall, an average of 11% of Puerto Rico's corals were damaged by the hurricanes; however, some sites experienced far more severe damage (up to 100%). The major reef-building and ESA-listed corals were the most severely impacted species: pillar coral (*Dendrogyra cylindrus*), elkhorn coral (*Acropora palmata*), lobed star coral (*Orbicella annularis*), and staghorn coral (*A. cervicornis*). The Northeast (including Culebra), North, Vieques, and West regions showed the highest levels of damaged corals, as might be predicted by the highest wave energies experienced in these regions due to the paths of the hurricanes. However, within a region there was considerable variability of damage between sites, likely due to particular site's exposure (i.e., orientation with respect the dominant wave direction) or amount and species of corals at that site.

Triage activities salvaged thousands of at-risk corals; however, thousands more are still likely at-risk. Further, in many cases, the fragments or loose colonies may have been removed completely from the reef site by the waves and are lost from the system. Thus, some sites would benefit from replanting the reef with propagated corals from nurseries to restore, or potentially enhance the protective services the reefs provide.

Introduction

In September 2017, Hurricanes Irma and Maria devastated the islands of Puerto Rico. In addition to the impacts the hurricanes had on land, they also had significant effects on Puerto Rico's coral reefs, which are the island's first line of defense against storm waves and flooding. Ad hoc surveys conducted post-hurricanes reported damage ranging from large coral heads being overturned or tossed into sand to extensive burial and breakage. In particular, known previously-dense thickets of the reef-building and Endangered Species Act (ESA) listed elkhorn coral (*Acropora palmata*; Figure 1a) showed significant colony breakage due to the species' branching morphology and location on the reef as a natural wave break (Figure 1b). Extensive damage was also observed to corals from the major Caribbean reef-building genus *Orbicella* spp. (star coral), that are also ESA-listed species (Figure 1c), in addition to other coral species. Thus, FEMA assigned NOAA to conduct an island-wide assessment of the impacts of the hurricanes on the coral reefs.

In addition to documenting the status of Puerto Rico's coral reefs after Hurricanes Irma and Maria, FEMA assigned NOAA to conduct emergency triage to salvage and reattach live corals that were still viable. Previous experience has shown that corals that have been physically impacted have a significantly greater chance of survival than those left unattached. It would take decades to regrow the large corals that were impacted, versus minutes to reattach it to the reef. Thus, concurrent with the assessment, emergency triage of highly-impacted reef sites was conducted.

Objectives

1. Describe status of Puerto Rican coral reefs after impacts from Hurricanes Irma and Maria
2. Identify sites as candidates for emergency coral triage
3. Identify of coral reefs that are potential long-term restoration candidates

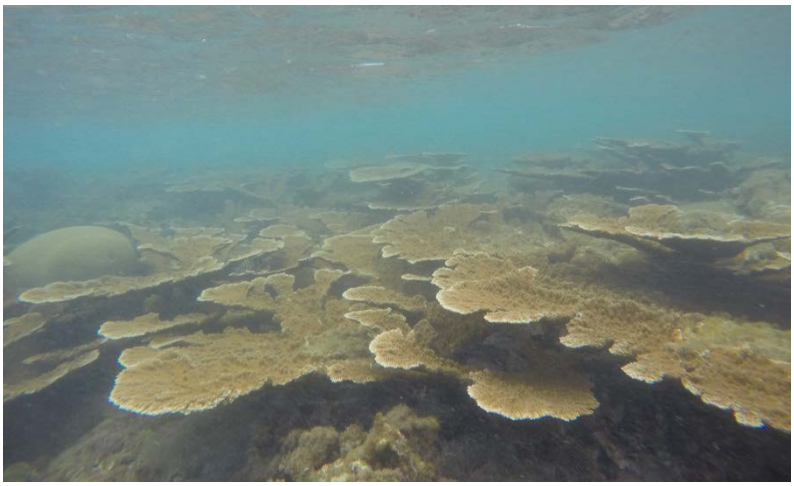

Figure 1a. Undamaged thicket of elkhorn coral (*Acropora palmata*). This ESA-listed species creates three-dimensional structurally complex reef that reduces wave energy and provides habitat for many coral reef species.

Figure 1b. Broken reef, damaged colonies, and fragments of elkhorn coral (*Acropora palmata*).

Figure 1c. Broken reef and lobes of lobed star coral (*Orbicella annularis*).

Methods

ASSESSMENT SITE SELECTION

Shallow coral reefs surrounding Puerto Rico were assessed using a probabilistic sampling design in order to satisfy all objectives outlined above. Site selection focused on "high value" reefs characterized by 1) coral cover, 2) ESA-listed coral species, and 3) contributions to coastal protection.

A probabilistic sampling design was used to allow for inferences from samples to the larger coral reef ecosystem likely to have been damaged by hurricanes. The sample frame covers all known shallow water coral reefs surrounding mainland Puerto Rico, Vieques, Culebra, and the islands within the NE Reserve corridor, and consists of a grid with individual cells measuring 50 x 50 m. The sampling grid was adapted from the National Coral Reef Monitoring Program (NCRMP) sample frame, which has been used since 2014 to monitor corals and fishes surrounding Puerto Rico. For this effort, the sample frame was narrowed to focus on coral-dominated habitats in depths less than 7 meters (m), which were those most impacted based on reconnaissance surveys.

To increase sampling efficiency and ensure representation from around the islands, the sample frame was stratified by the storm path, discrete coral reef habitats, and geographic region. Sample effort was allocated to ensure approximately equal field effort was allocated to sites shallower than 3.5 m and sites 3.5 - 7 m depth. A total of 150 primary sites were allocated into strata proportional to area such that the following regional effort requirements are met (Table 1). Additional sites per region were identified to serve as alternative sites for primary sites that could not be assessed or did not meet the described criteria.

Table 1. Number of planned sites per geographic region.

Regions	Number of Sites
North	20
West	15
SW	15
SE	20
NE Reserve/East PR*	30
Culebra*	30
Vieques	20
TOTAL	**150**

A total of 147 of the goal of 150 sites were surveyed. Weather constraints and water visibility precluded meeting the sampling goal for the Southeast Region. The following maps show the locations of the assessments. *Culebra and the NE Reserve/East PR sites were combined for analyses.

DIVER-BASED CORAL IMPACT ASSESSMENT SURVEYS

The assessment surveys consisted of two types of in-water diver surveys: a transect survey and a roving survey. The transect survey sites were based on a stratified random sample design to allow for statistical representation of areas that have not been surveyed. Divers conducted a line-transect survey (as described below) at pre-selected site coordinates. The roving survey provided an overview of a larger area where divers could specifically targeted reef areas outside of the assessment transect that may have had impacts. Roving surveys were also conducted at nonrandom locations informed by expert knowledge of high coral cover of priority species or expected damage.

Only sites that met predetermined criteria were surveyed. Sites for surveys were required to have colonized hard-bottom habitat greater than 10% and were required to contain coral. The assessment survey was conducted whether damage was present or not. If the site did not meet the criteria requirements, surveyors recorded the reason on the datasheet and did not survey the site.

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 site or impacts. Each assessment diver conducted a 50 m meter long by approximately 5 meter wide belt-transect bisecting the survey grid cell (Figure 2), mindful of the direction of current and bathymetry, and minimizing diver separation for safety. Transect length (L) and width (W) were recorded (m) by each diver. The transect area may have been truncated (shortened or narrowed), or broadened (widened) as necessary due to visibility, field conditions (e.g. surge, high damage, high coral cover), or habitat. Any changes were noted on the datasheet. Video was taken of the transect line area to capture the footage for reference.

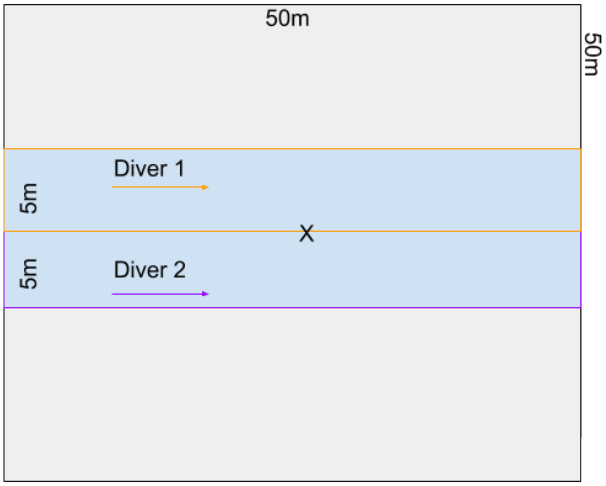

Figure 2. Representation of 2 diver survey areas (5m x 50 m) within a sampling grid cell (50m x 50m). X marks the survey centroid GPS coordinates and location of diver descent.

Roving surveys were conducted outside of the assessment survey area to scout for impacts over a broader geography in order to locate reefs that needed additional triage or restoration. Two divers towed a GPS (recording the trackline). Divers recorded survey beginning and end times to use for clipping the GPS trackline. Roving surveyors also noted the width of their survey area on their datasheets. Survey area was calculated from the width and length and used in analyses. Areas of note were marked by time or by GPS point.

The following categorical evaluations were made at each assessment site and roving survey area: damage to site, damage to corals and/or framework, potential as a triage site, potential as a long-term restoration site (Table 2). To inform the triage team, assessment surveyors estimated the number of unattached corals estimated in the 50m x 50 m site, and roving surveyors estimated the number of loose corals in a different, but specified survey area (Table 2). An estimate of rubble area at the site was also made because surveyor observations and local information indicated that large areas of reef have been pulverized to rubble, and are no longer reef habitat.

Table 2. Site-level assessment survey classifications and descriptors.

Site-level descriptor	Data type
Survey depth (ft)	Mean depth of surveyed area
Transect heading	Direction of transect orientation
Viz	Visibility of water (m)
Hard-bottom habitat	Estimate of % in transect area Estimate of % in 50 x 50 m site (must be > 10% colonized HB for survey to proceed)
Dominant habitat type	Dominant reef habitat type: aggregate reef, patch, pavement, bedrock
	Estimate (%) within transect area
	Estimate (%) within 50 x 50 m site
Rubble (%)	Estimate of area of rubble as percent (%) of benthos
Estimated # of loose corals	Estimate in 50 x 50 m site
	Estimate in surrounding area (estimate of area in m^2)

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 Triage	High = > 300 corals to be reattached (greater than 20 cm); many ESA species impacted
	Medium = > 100 corals to be reattached (greater than 20 cm); some ESA 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 by surveyors

The assessment and impacts surveys focused on selected reef-building coral species (Table 3) that contribute to coastline protection, had the greatest population decline, and with the greatest restoration potential, although surveys included all species to be representative of the community. All corals and fragments greater than 20 cm in size (or with 20 cm of live tissue) were recorded in the survey. All observed corals were counted by size class (Table 4). Bleaching and disease were identified as present or absent. This survey focused on breakage and did not include abrasion due to the time elapsed since the storms resulting in turf algae colonization of exposed coral skeletal surfaces. Fragments of branching coral (i.e., pieces of *Acropora* corals) were categorized as either attached to the substrate (attached fragments) or unattached (loose fragments), and categorized as either dead or live if live tissue was present. Upside down, overturned, or loose colonies with at least 20 cm of live tissue (e.g. pillars of pillar coral [*Dendrogyra cylindrus*], lobes of lobed star coral [*Orbicella annularis*]) were identified by species and size class. For branching corals that have grown from colonies into thickets greater than 1.5 m, species were identified, and the maximum thicket length (m) and width (m) were estimated so that thicket area could be calculated. A percentage of thicket damage was also estimated.

Table 3. Targeted coral species for coral impact assessment surveys.

Targeted coral species	
Acropora cervicornis	*Montastraea cavernosa*
Acropora palmata	*Orbicella annularis*
Acropora prolifera	*Orbicella faveolata*
Colpophyllia natans	*Orbicella franksi*
Dendrogyra cylindrus	*Porites* spp. (branching only)
Diploria labyrinthiformis	*Pseudodiploria strigosa*

Table 4. Targeted coral species for coral impact assessment surveys. (Right) Size categories for corals to be included in survey.

Size category	**Size range (cm)**
Medium	20 - 50
Large	51 - 100
XL	101-150
Gigantic	> 151

DIVER-BASED CORAL TRIAGE

A proportion of corals broken loose or fragmented by the hurricane can remain alive on the bottom, but are at risk of being tumbled by subsequent storm waves, which will continue to reduce the amount of live coral on a reef. By conducting coral triage, these loose at-risk corals can be reattached to the reef substratum to minimize the overall hurricane damage at local scales. Triage was conducted at sites identified with the highest level of damage by both reconnaissance and formal assessment surveys focusing on locations with the highest cost benefit. A team of no less than 4 trained divers navigated to the predetermined triage site and prepared gear (e.g., crates, lift bags) and materials (e.g. cement, marmolina) for triage activities. Preparations were made based on the expected numbers, sizes, and species of corals to be reattached at the particular site. Once in the water, divers distributed themselves around the site to begin triage activities.

In general the goal of triage was to rescue damaged coral fragments and colonies within the site by returning the coral to a proper orientation and securing it to the bottom. Appropriate locations with open hardbottom were identified to reattach loose so as not to disturbed the existing undamaged corals present. Corals and fragments were temporarily cached near restoration locations prior to reattachment. Cement was used to re-attach corals to the substrate. The reef surface was cleaned of turf algae and sediment prior to reattachment to provide for successful adhesion of cement.

In some cases, the habitat at the damaged site was not suitable for reattaching the damaged corals (i.e. reduced to rubble). In those cases the coral fragments were collected and moved to an alternative site better-suited for long-term survival of the corals.

Results

Assessment Surveys

The assessment team surveyed 153 sites in 38 field days from February 27th to May 7th, 2018 (Figure 2). A total of 414,354 m^2 was surveyed, with an 11,300 m^2 area included in transect surveys (n = 147) and 403,054 m^2 (n = 143) in roving diver surveys. A total of 80,297 corals were counted by the assessment team: 27,410 corals in transect surveys, and 52,887 corals in roving diver surveys.

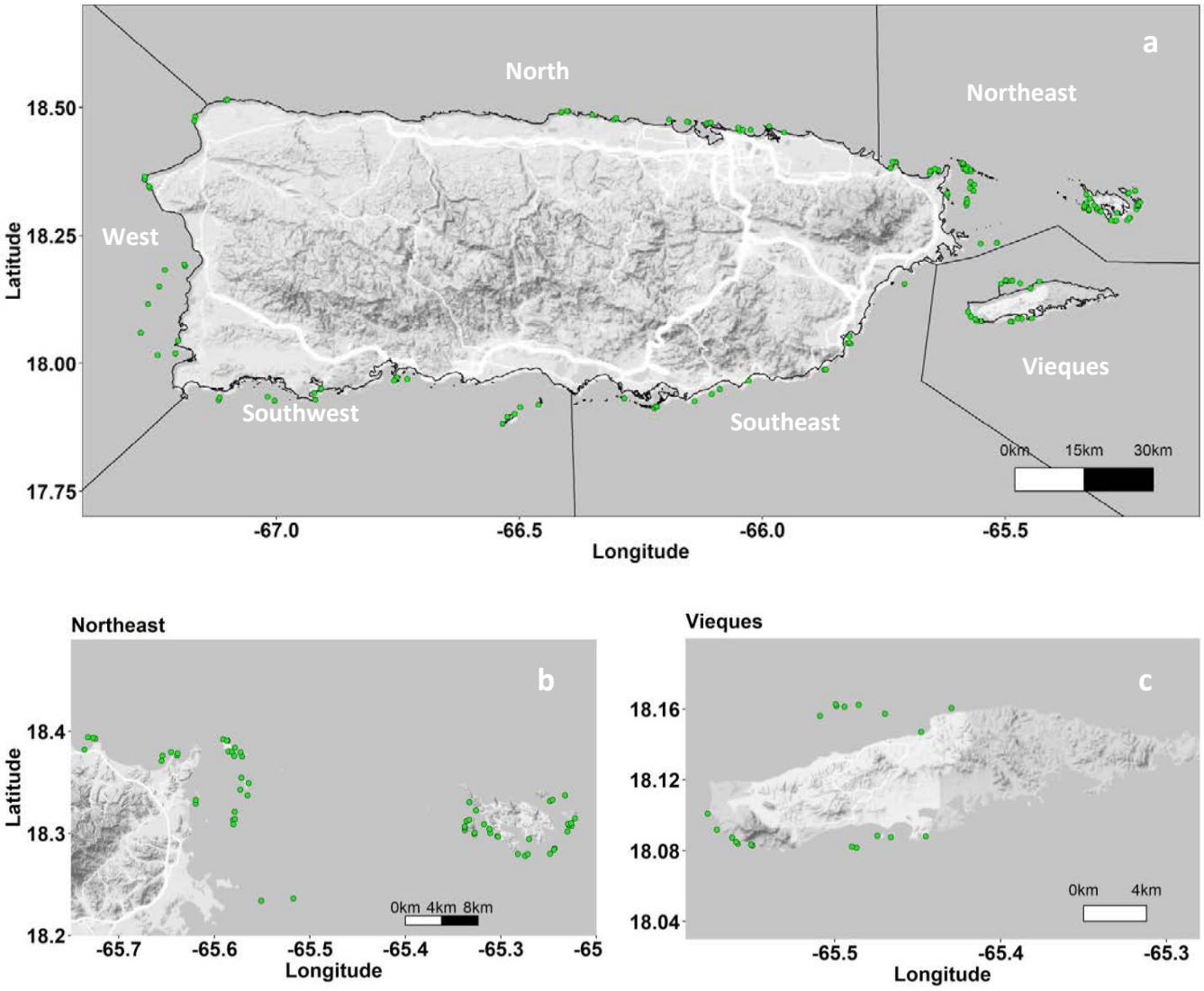

Figure 3. All coral assessment sites around Puerto Rico (a). Coral assessment sites in the Northeast (b) and Vieques (c).

Summary by Region

Based only on the random transect surveys, region-wide, the Northeast and Vieques regions showed the highest levels of damaged corals, as quantified by proportion of damaged corals (Figure 3) and mean density of damaged corals (Figure 5) . Based on the roving diver surveys, which specifically targeted reef areas outside of the assessment transect that may have had impacts, the Northeast, North, Vieques, and West regions showed the highest levels of damaged corals, as quantified by proportion of damaged corals (Figure 4).

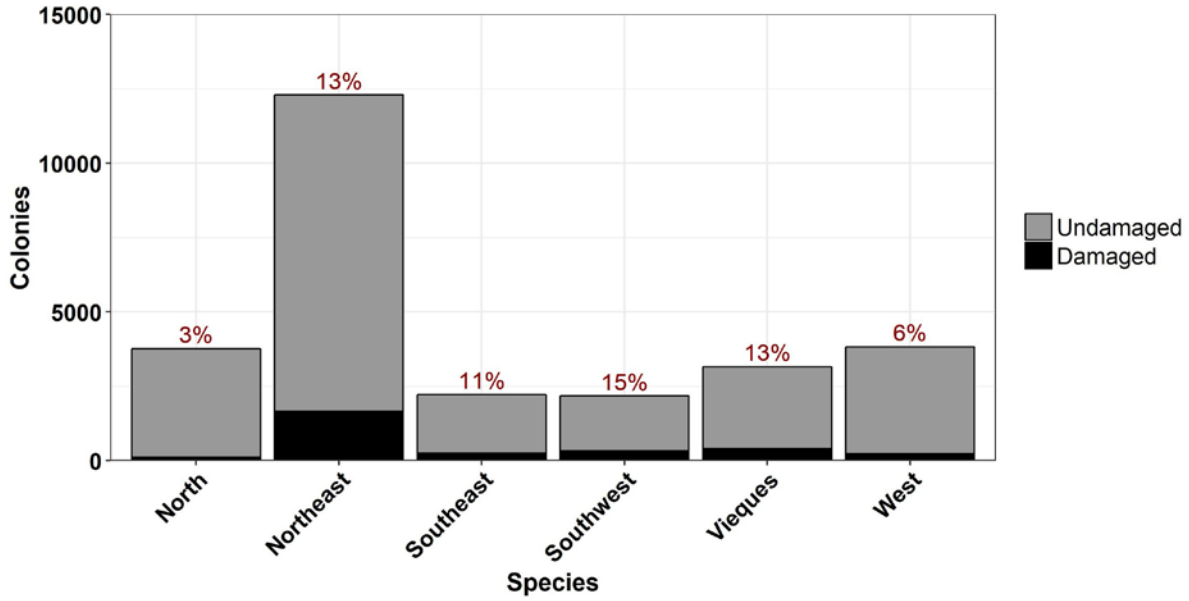

Figure 4. Regional comparison of damaged and undamaged colonies based on transect surveys. Values in red indicate the prevalence of damaged colonies. The northeast region had the highest number of both undamaged and damaged corals.

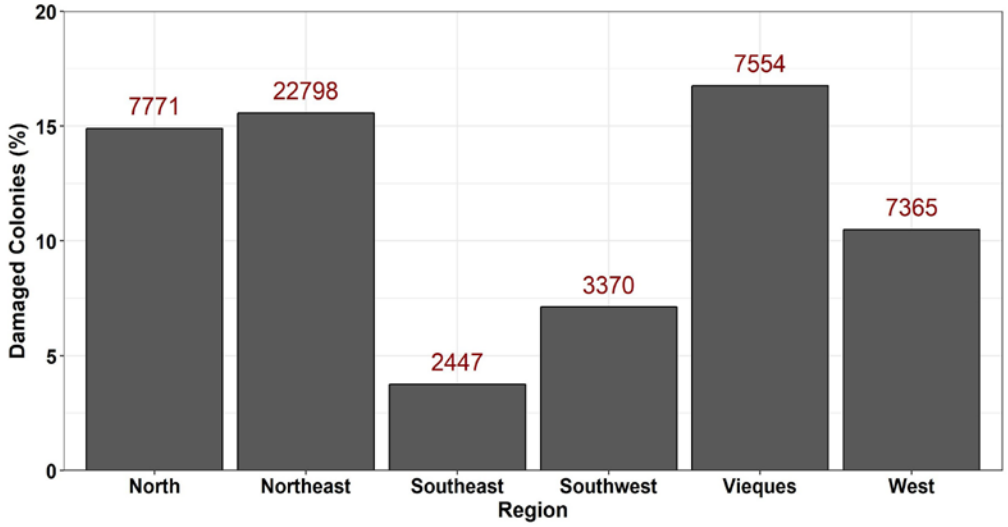

Figure 5. Regional comparison of prevalence of coral damage by region in roving diver surveys. Values in red indicate the total number of colonies (damaged and undamaged). *Note: Roving diver surveys targeted likely damaged areas.*

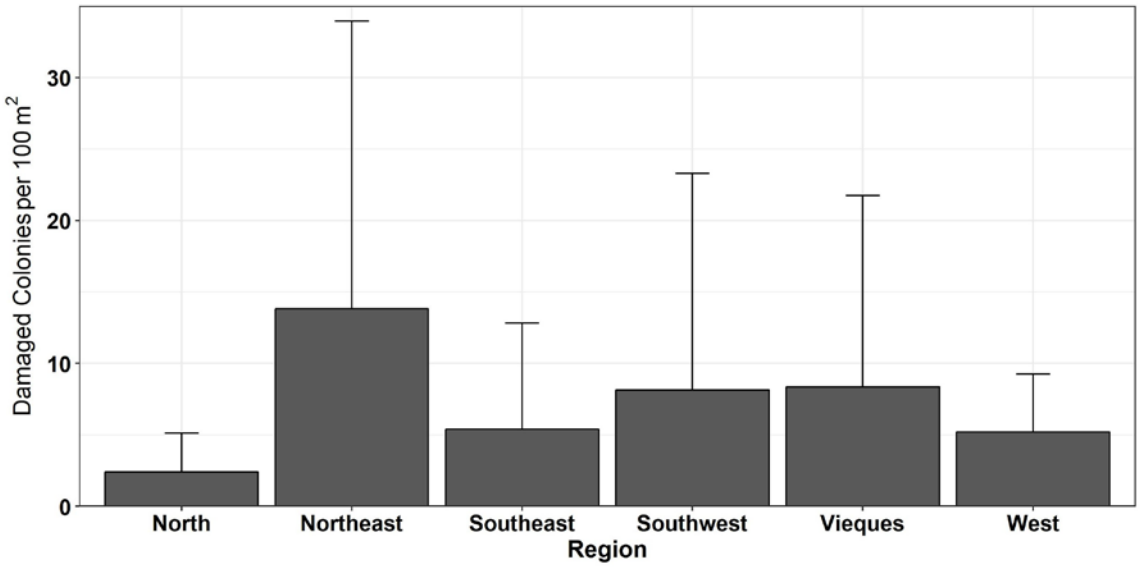

Figure 6. Regional comparison of mean density of damaged corals (colonies per 100 m2) based on transect surveys. Error bars represent standard deviations.

Summary by Species

For reefs in Puerto Rico, 11% (2,958 of 27,410) of corals in transect surveys showed coral damage where the colony was broken, overturned, upside down or loose. In addition, 1,380 branching coral fragments were counted; most fragments (994; 72%) were elkhorn coral. Medium-sized coral colonies (20 - 50 cm) had the largest number of damaged colonies, although large (50 - 100 cm) and extra-large (100 - 150 cm) corals had the greatest proportion of damage to colonies (15%; Figure 7).

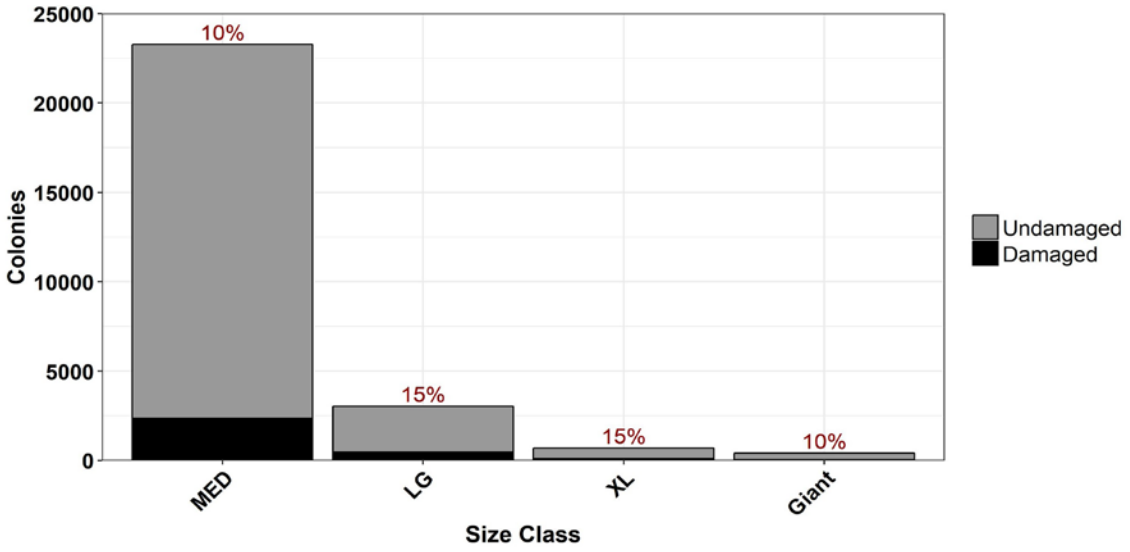

Figure 7. Size of coral colonies showing damage. Medium colonies (20-50 cm) had the largest number of colonies surveyed with damage and without damage. Large (50-100 cm) and extra-large (100 - 150 cm) colonies had fewer colonies surveyed, but the greatest proportion of damaged to undamaged colonies.

By species (Figure 8), the ESA-listed pillar coral sustained the highest frequency of occurrence of damage (*Dendrogyra cylindrus* [DEN CYLI]: 77% of 117 colonies showed damage; Figure 9a), followed by the branching finger coral (*Porites* species: *P. porites*, *P. divaricata*, and *P. furcata* [BR POR SPP]; 47% of 942 colonies showed damage; Figure 9b), ESA-listed elkhorn coral (*A. palmata* [ACR PALM]*:* 45% of 421 colonies showed damage; Figure 9c), ESA-listed lobed star coral (*O. annularis* [ORB ANNU]: 43% of 1548 colonies showed damage; Figure 9d), and ESA-listed staghorn coral (*A. cervicornis* [ACR CERV]: 37 % of 165 colonies showed damage; Figure 9c). Mustard hill coral (*Porites astreoides* [POR ASTE]) and symmetrical brain coral (*Pseudodiploria strigosa* [PSE STRI]) were the most frequently observed corals; however, although both species had a low frequency of damaged corals relative to undamaged corals, (3% and 9%, respectively), a high number of symmetrical brain corals were damaged (Figure 8).

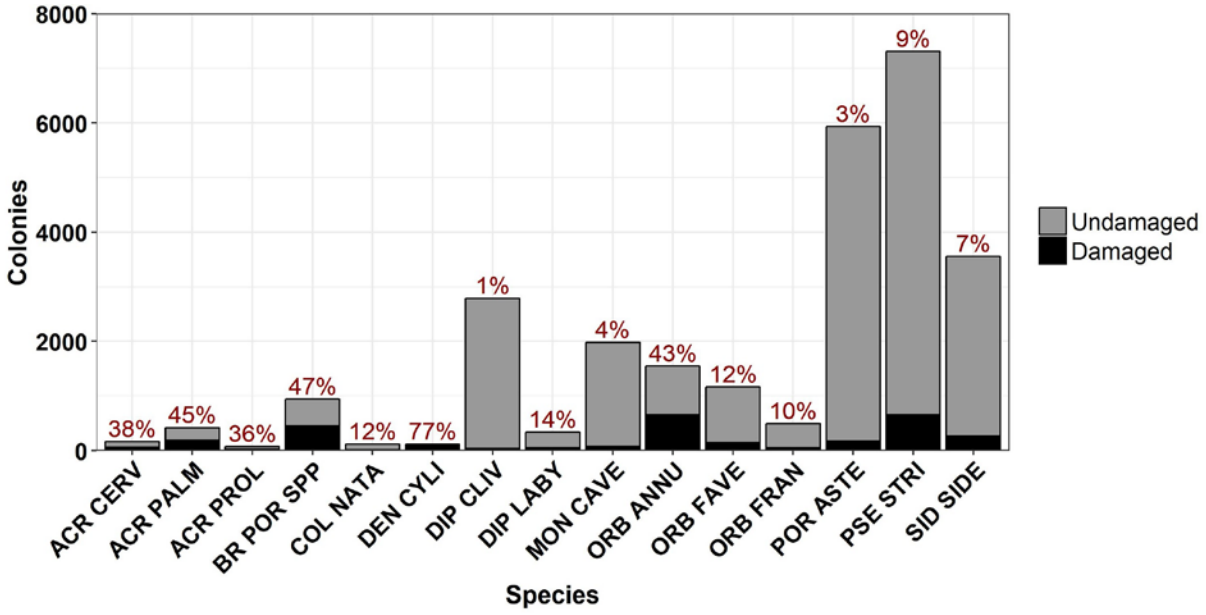

Figure 8. Damage by coral species counted in impact assessment surveys. Red values indicate damage prevalence (percentage of total colonies with damage).

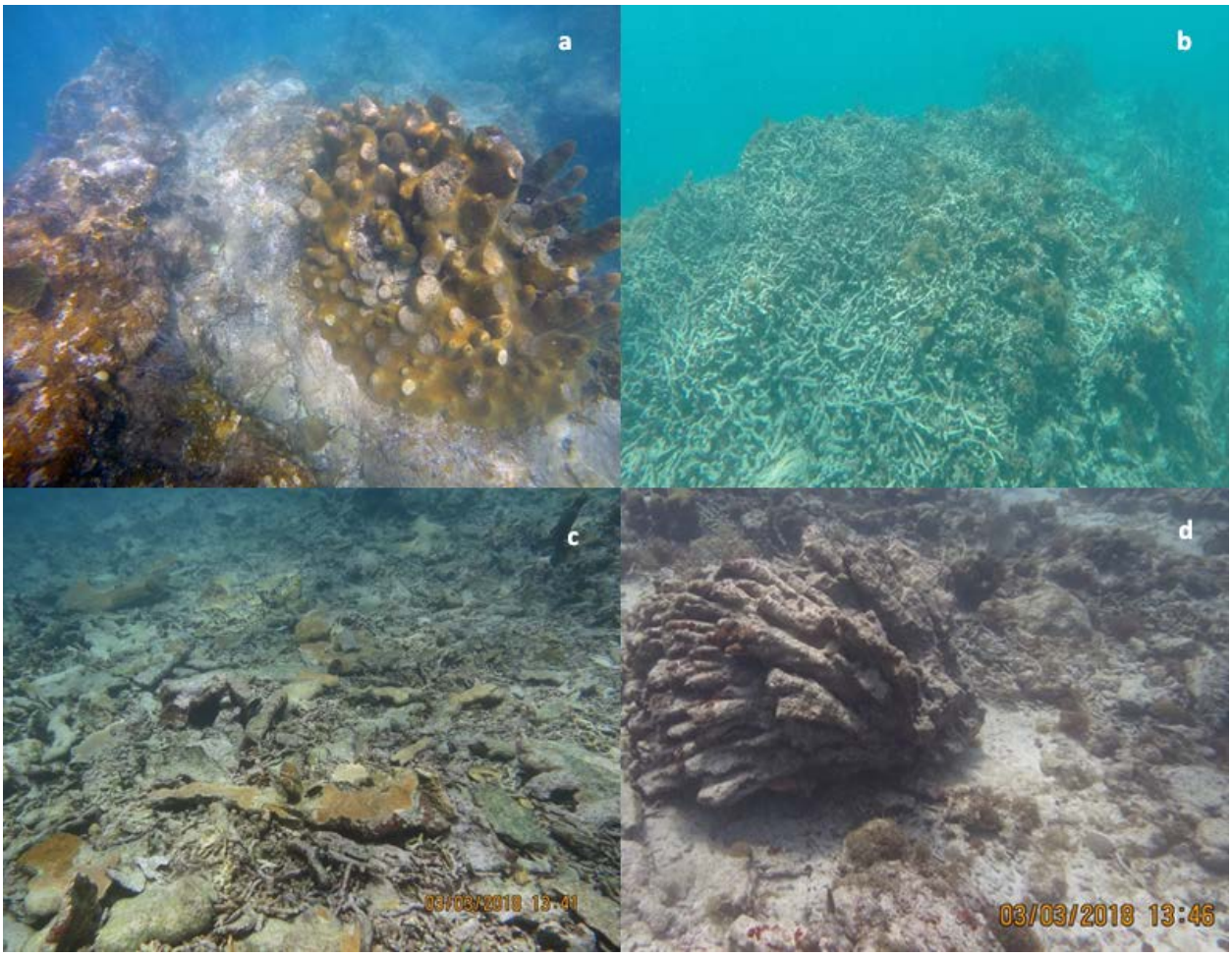

Figure 9. Large colony of pillar coral (*Dendrogyra* cylindrus) with most of its pillars sheared off (a). Thicket of branching finger coral (*Porites* spp.) that was broken up to loose rubble; macroalgae now covers part of the rubble (b). Fragments of elkhorn (*Acropora palmata*) and staghorn (*A. cervicornis*) broken by wave energy (c). Large colony of lobed star coral (*Orbicella annularis*) that was overturned and loose (d).

Overall, 1,377 coral fragments were counted during transect surveys. Of these, 991 were elkhorn corals (*A. palmata*), 174 were branching finger corals (*Porites* spp.), 151 were staghorn corals (*A. cervicornis*), 46 were hybrid staghorn-elkhorn corals (*A. prolifera*), and 14 were pillar corals (*D. cylindrus*).

Elkhorn coral (*A. palmata*) and lobed star coral (*O. annularis*), both listed as threatened under the ESA, are two coral species that are major contributors to creating complex three-dimensional coral habitat that can provide shoreline protection. These two species showed both high occurrence of damage (Figure 8) and high density of damage and (Figure 10).

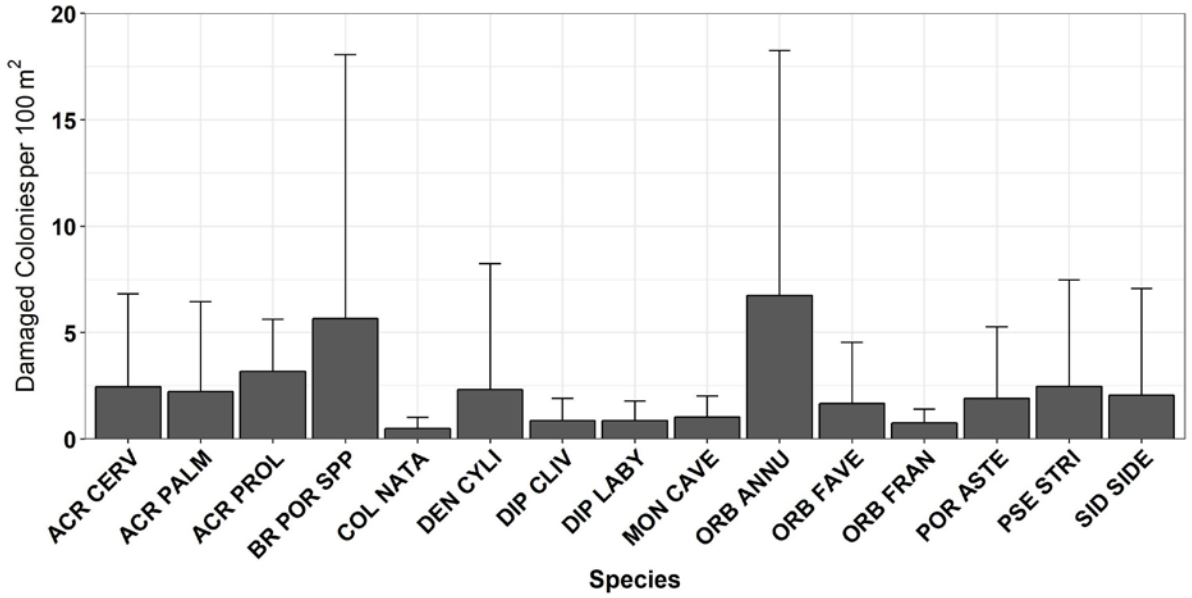

Figure 10. Mean density of damaged coral colonies by species (colonies per 100 m2). lobed star coral (O. annularis; ORB ANNU) and branching finger coral (Porites spp.; BR POR SPP) had the highest density of damaged colonies.

For elkhorn coral, damage 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. A total of 14 sites were categorized with severe damage to elkhorn corals. These sites were located in the Northeast (including Culebra), North, and West regions (Figure 11). Two of the five sites (Figure 11c) with the highest levels of damage are north of San Juan and east of Fajardo, two population centers. Additional details on damaged corals at these five sites are provided in Appendix 3.

For lobed star coral (*O. annularis*), damage 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. A total of 5 sites were categorized with severe damage to lobed star corals. These sites were located around Culebra in the Northeast regions (Figure 12). Additional details on damaged coral species at these five sites are provided in Appendix 4.

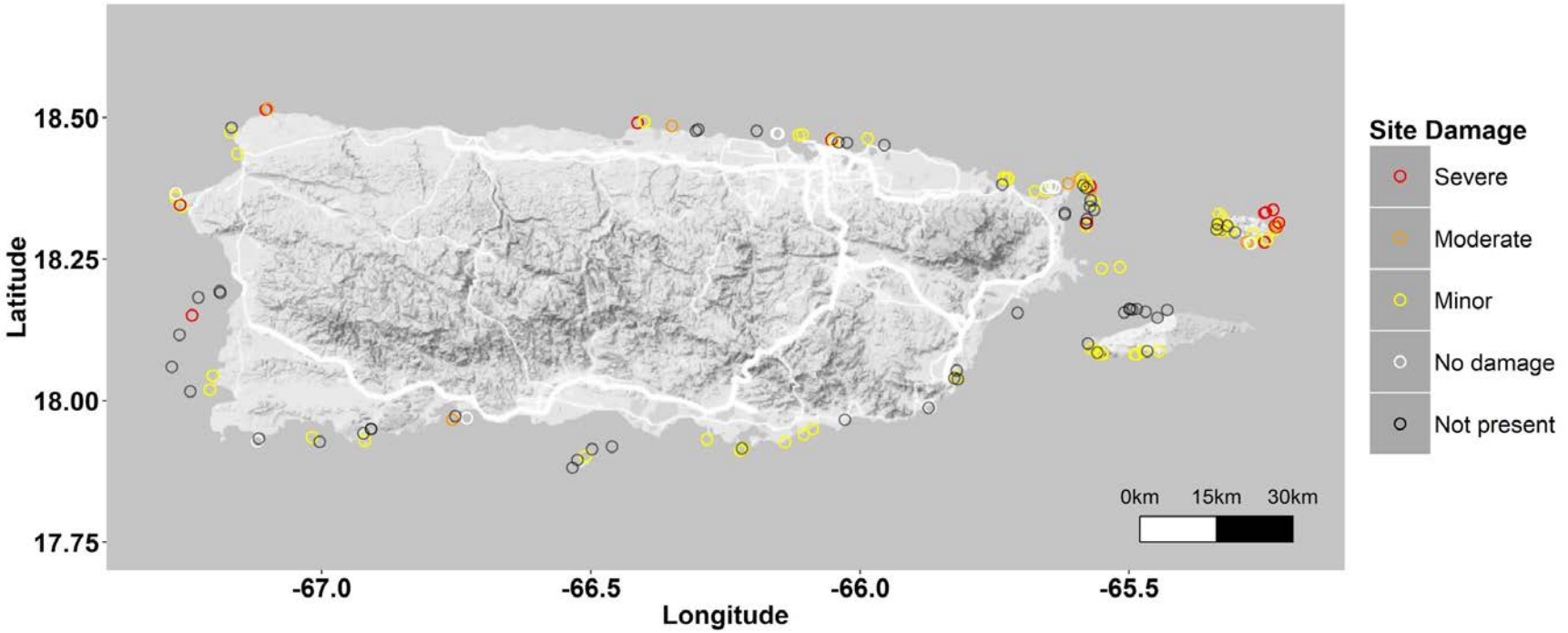

Figure 11a. Damage to elkhorn coral (*A. palmata*) at all survey locations around Puerto Rico. Severe damage (red circles) was defined as more than 100 broken colonies and fragments at a site. Moderate damage (orange circles) was defined as a site with 50 - 99 broken colonies and fragments, and minor damage (yellow circles) was defined as a site with 49 or fewer broken colonies and fragments. Sites with no damage or where A. palmata was not present are also indicated. A total of 14 sites were categorized with severe damage.

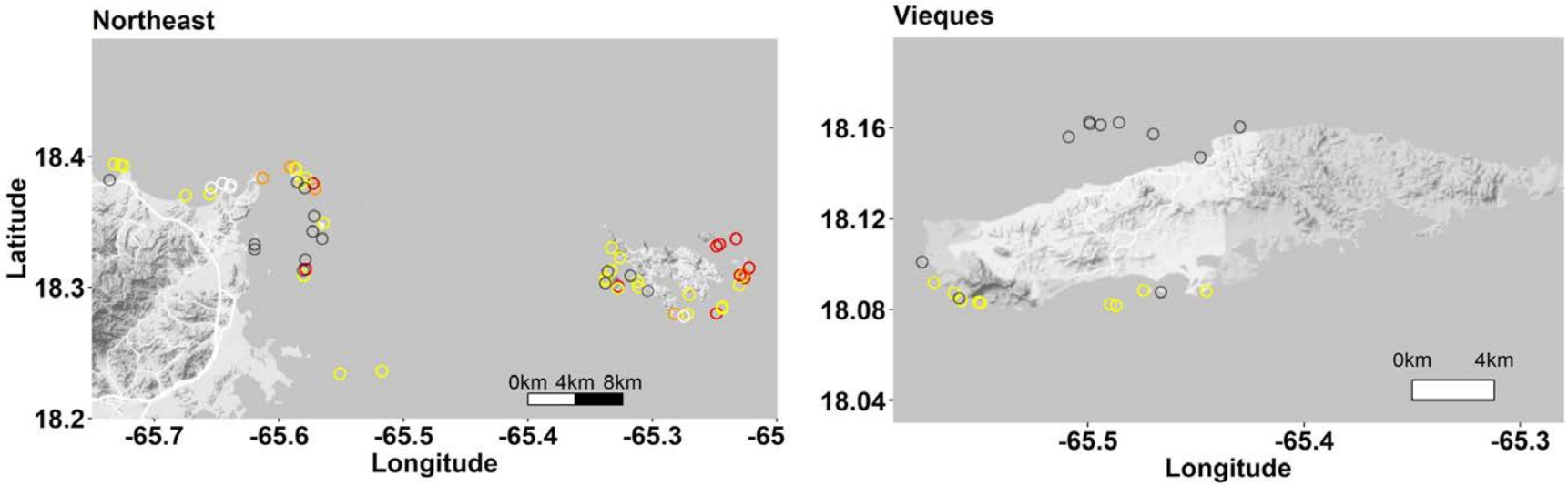

Figure 11b. Damage to elkhorn coral (*A. palmata*) in the Northeast and Vieques regions.

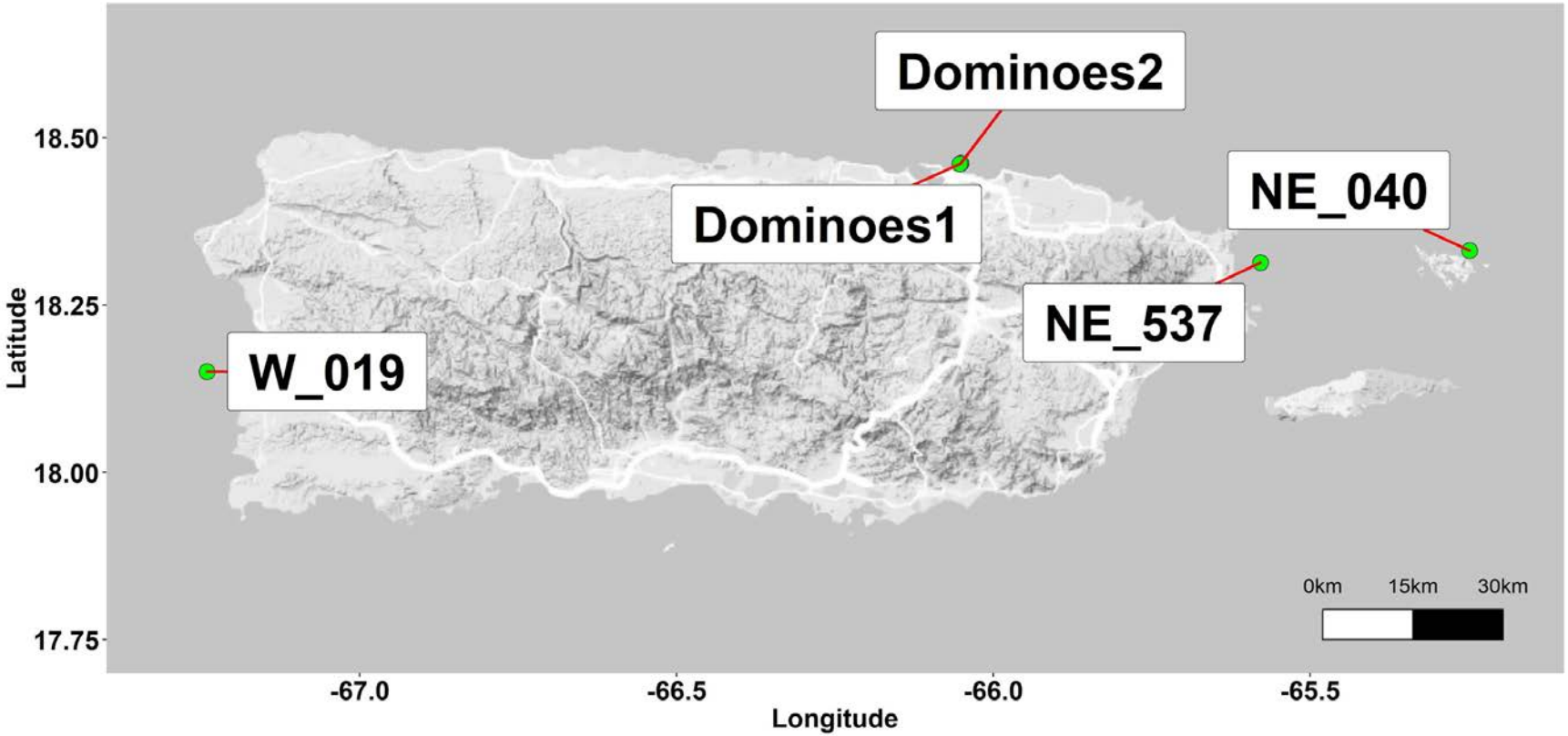

Figure 11c. The five sites with the most severe damage to elkhorn coral (*A. palmata*) at all survey locations around Puerto Rico. Additional information on these sites is in Appendix 3.

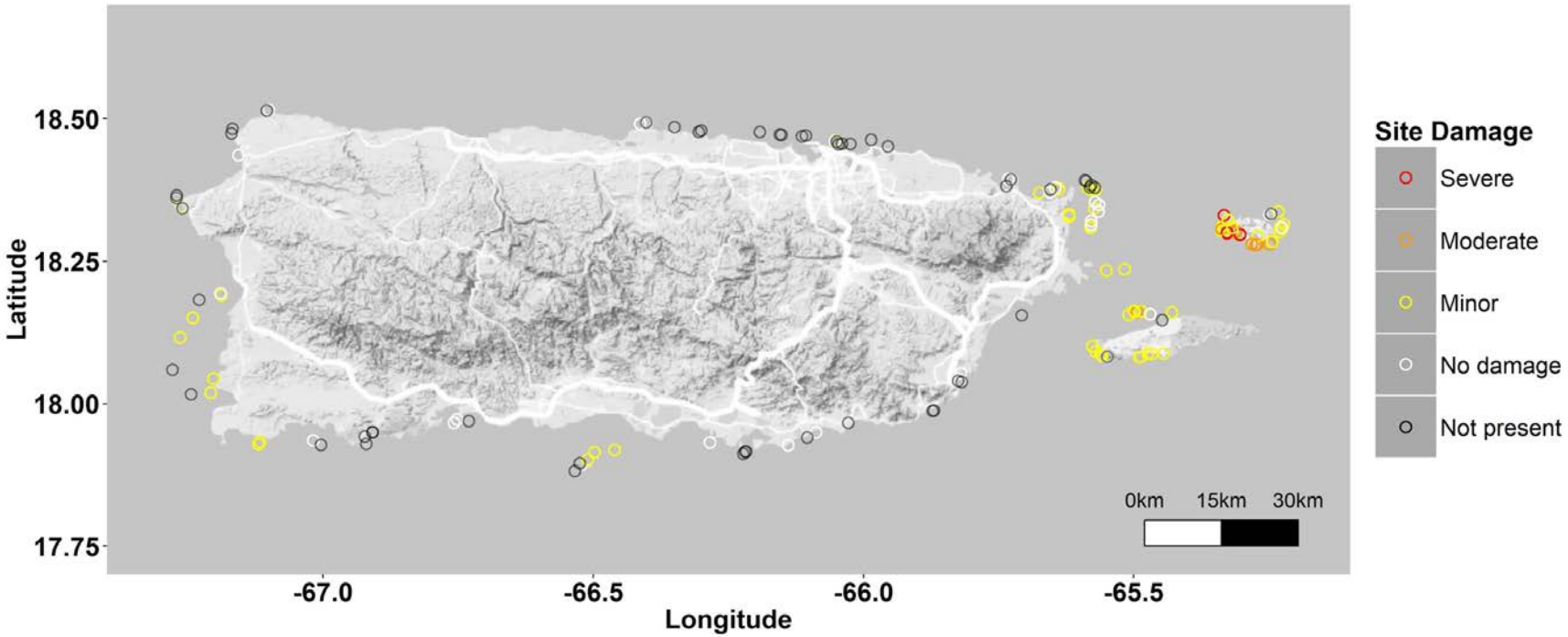

Figure 12a. Damage to lobed star coral (O. annularis) at all survey locations around Puerto Rico. Severe damage (red circles) was defined as more than 100 broken colonies and fragments in the Impact and Roving surveys combined. Moderate damage (orange circles) was defined as 50 - 99 broken colonies and fragments, and Minor damage (yellow circles) was defined as 49 or less. Sites with no damage or where O. annularis was not present are also indicated. A total of 5 sites, all near Culebra, were categorized as severely damaged.

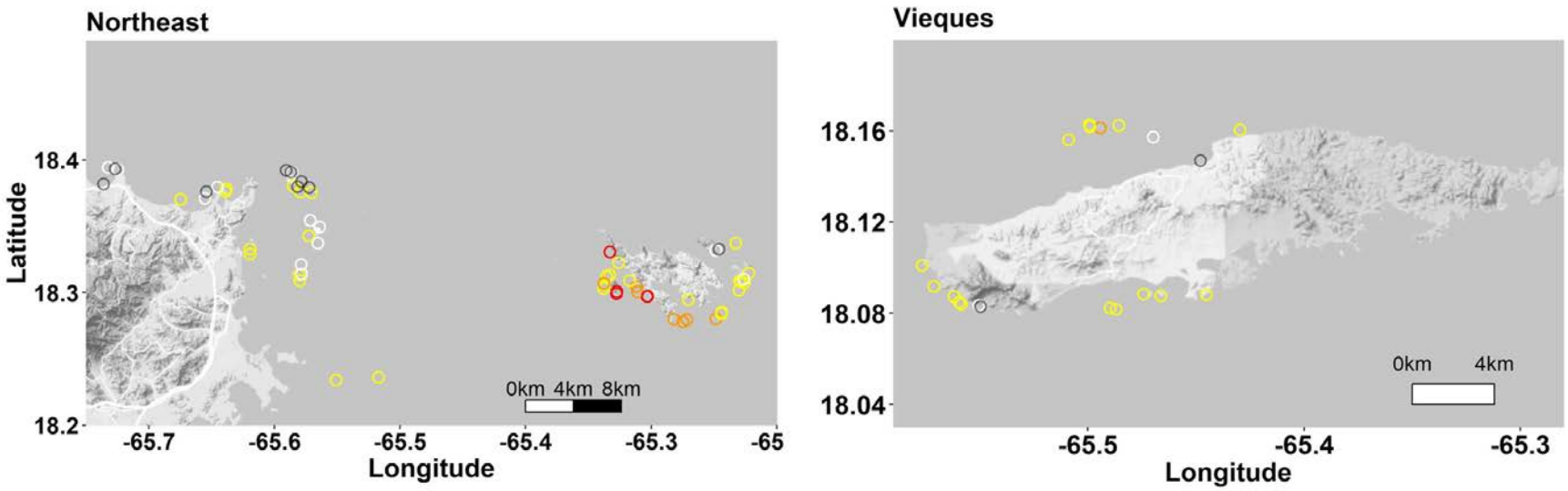

Figure 12b. Damage to lobed star coral (*O. annularis*) in the Northeast and Vieques regions.

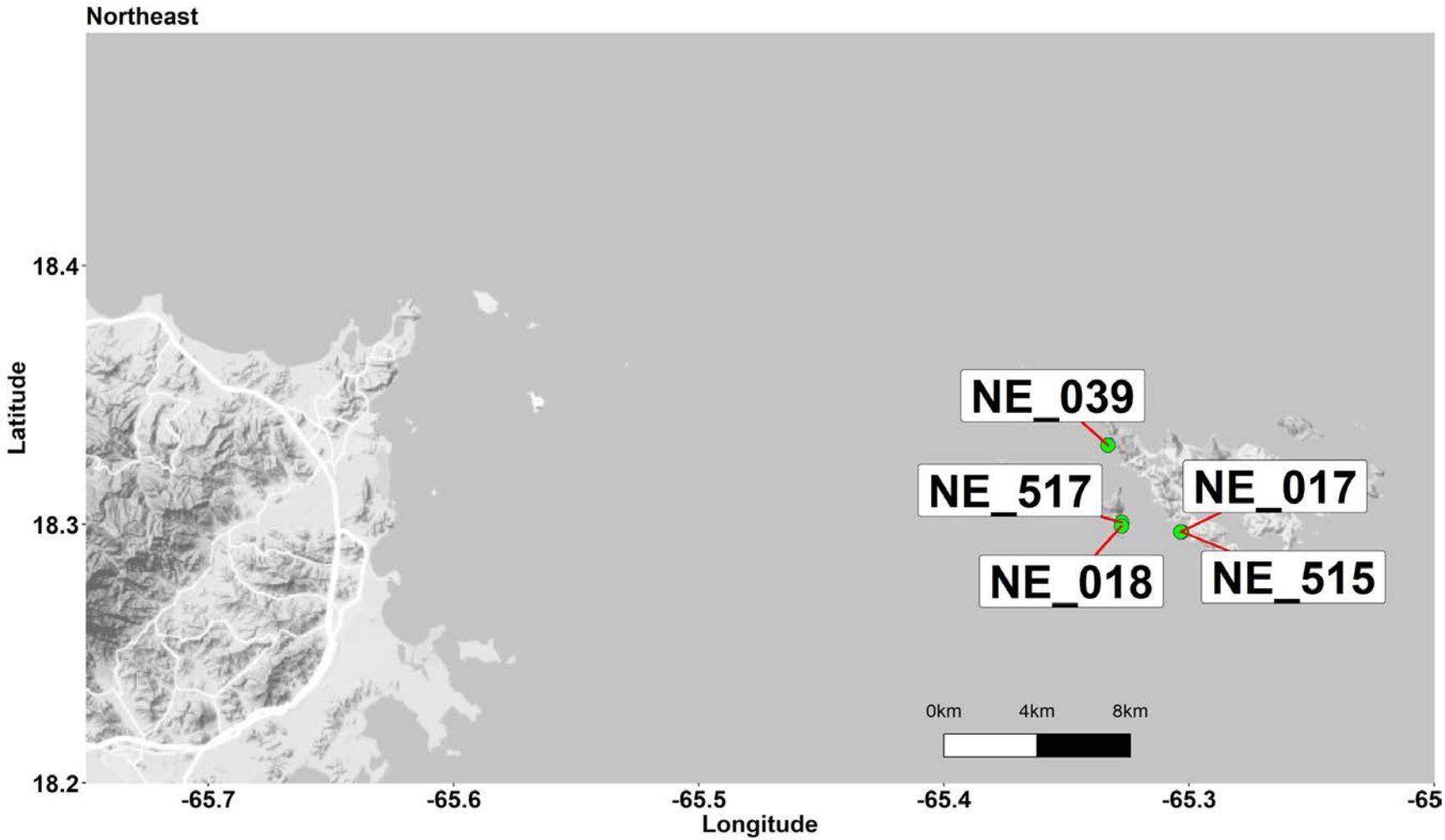

Figure 12c. The five sites with the most severe damage to lobed star coral (*O. annularis*) at all survey locations around Puerto Rico. Additional information on these sites is in Appendix 4.

Coral Triage

A total of approximately 5,400 corals have been reattached at 32 sites to date (Figure 13). This work was accomplished in 40 field days from February 27th to May 8th, 2018. Triage work will continue for approximately 20 additional field days during this mission assignment. Updated counts of corals reattached and sites will be provided once triage work is complete.

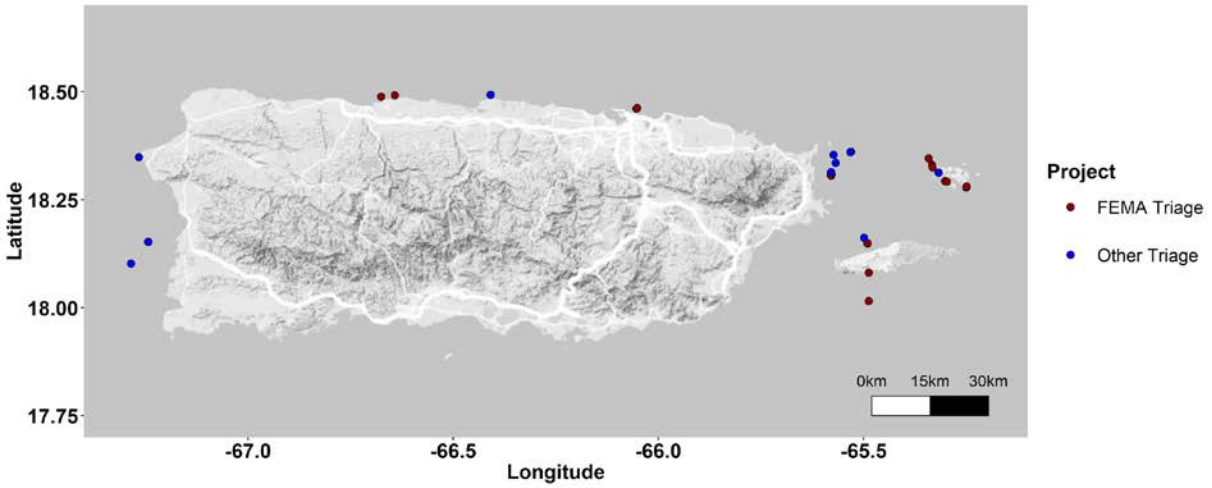

Figure 13a. Locations where triage has been conducted as of May 7, 2018. Red dots indicate the 32 sites where triage was conducted under this mission assignment. Blue dots indicate where triage was conducted prior to this mission assignment.

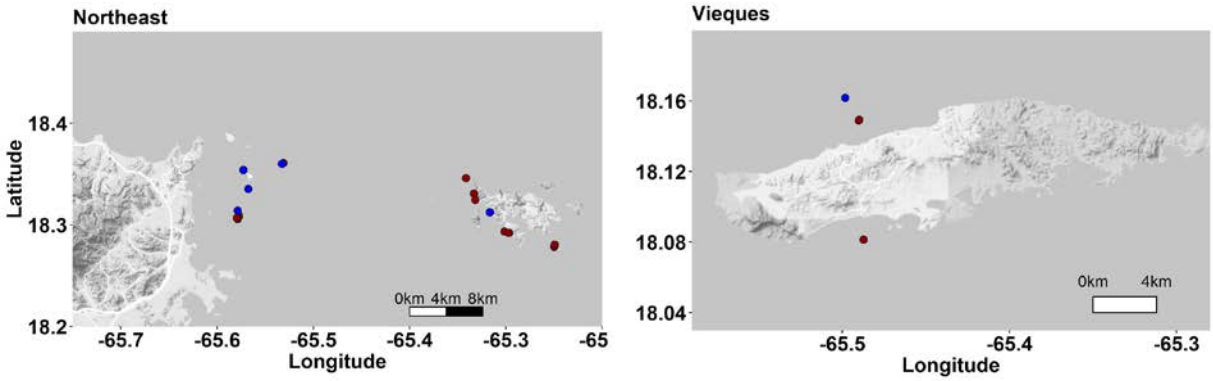

Figure 13b. Locations where triage has been conducted as of May 7, 2018. Red dots indicate the 32 sites where triage was conducted under this mission assignment. Blue dots indicate where triage was conducted prior to this mission assignment.

Triage activities were primarily conducted in the Northeast (including Culebra) and Vieques regions. Recently, based on the assessment surveys, triage activities have begun in the North. All triage sites were identified as having had severe damage and large numbers of still-live fragments or unattached

colonies. Triage focused mainly on the following reef-building species: *Acropora palmata*, *Orbicella* spp., *Dendrogyra cylindrus*, *Pseudodiploria* spp., *Diploria* spp., *Colpophyllia natans*, and *Porites astreoides* (Figure 14).

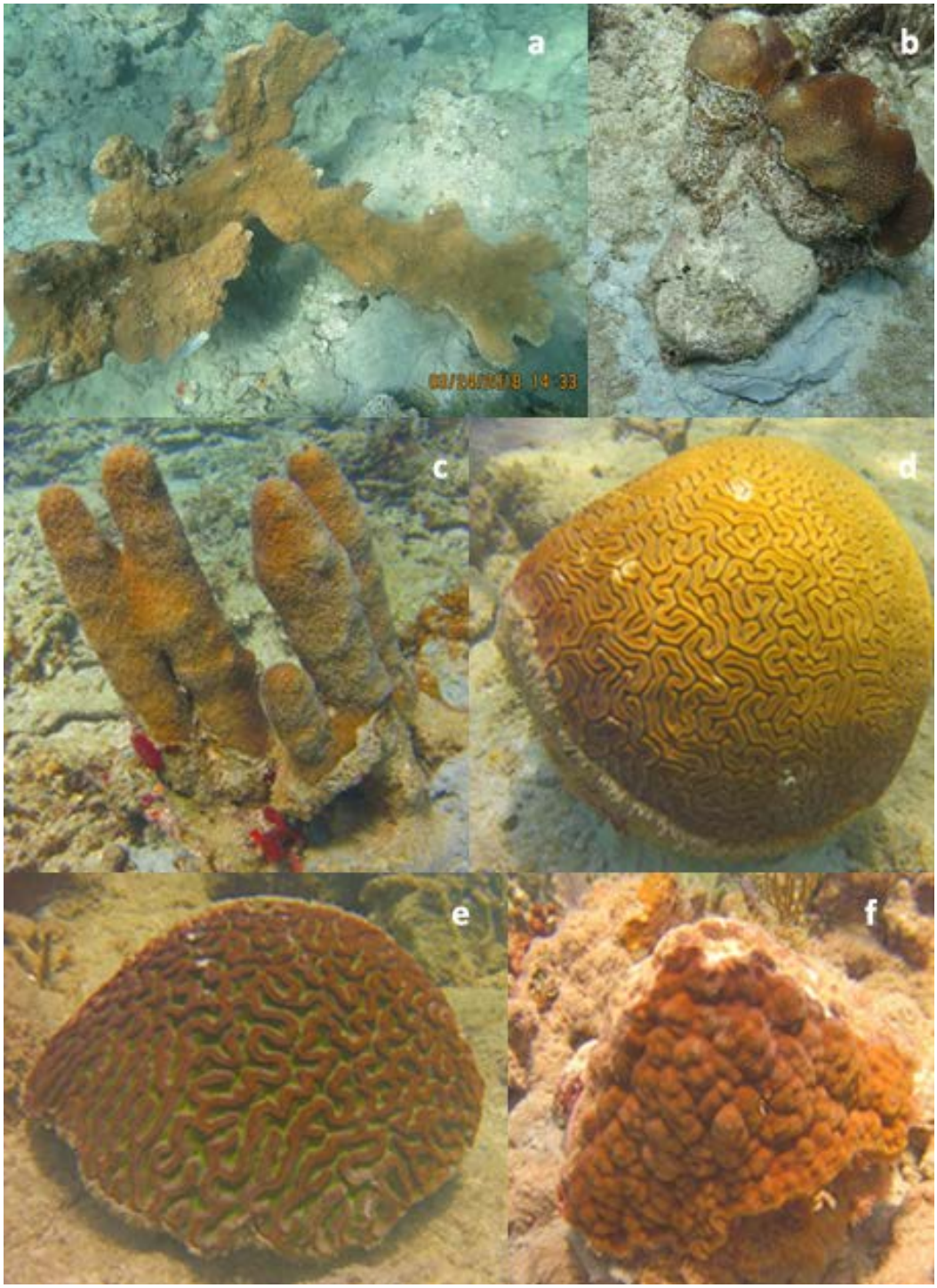

Figure 14. Corals stabilized by the triage team. Elkhorn coral, *Acropora palmata* (a); lobed star coral, *Orbicella annularis* (b); pillar coral, *Dendrogyra cylindrus* (c); grooved brain coral, *Diploria labyrinthiformis* (d); lobed brain coral, *Colpophyllia natans* (e); mustard hill coral, *Porites astreoides* (f).

Discussion

There are 756 km^2 of coral reef and hard-bottom habitat within the waters around the islands of Puerto Rico {Kendall et al. 2001}. Coral reefs buffer coastlines from erosion and inundation, providing important protective services. These natural coastal systems reduce risk to people and infrastructure from wave damages and flooding. Globally, coral reefs reduce wave energy by 97% and reduce wave height by 84% (Ferrario et al. 2014). Puerto Rico's coral reef system also provides ecosystem and fishery services. The majority of the island's coasts are at mercy of sea level rise and storm surge abatement. The main natural defense for Puerto Rico's coasts are its coral reefs, mainly structured by ESA-listed coral species, such as elkhorn (*Acropora palmata*), staghorn coral (*A. cervicornis*), and lobed star coral (*Orbicella annularis*).

The ESA-listed coral species elkhorn coral (*A. palmata*), staghorn coral (*A. cervicornis*), pillar coral (*D. cylindrus*), and lobed star coral (*O. annularis*) as well as the branching *Porites* species appear to have experienced the greatest negative impact from Hurricanes Irma and Maria in terms of colonies damaged and number of fragments created. Although many of these species reproduce through and can benefit from fragmentation, fragments are more likely to develop into healthy adult colonies if triage and restoration techniques are used (Lirman, 2000; Griffin et al., 2015). Furthermore, damaged colonies may be more susceptible to bleaching, disease, boring organisms and algae overgrowth; therefore it is essential that restoration efforts be applied to recover the capacity of these nearshore shallow water reefs systems to provide effective protection to coastal infrastructure.

Based on the random transect surveys, coral reef sites that experienced the most severe damage were found in the Northeast (including Culebra), North, and West regions. Based on the roving diver surveys, which were purposely looking for damage, the Northeast, North, Vieques, and West regions all sustained approximately double the damage than the Southeast and Southwest. These results are consistent with areas that likely experienced highest wave energy due to the paths of Hurricanes Irma and Maria. However, within a region sites experienced varying levels of damage. This may be based on the particular site's exposure (i.e., orientation with respect the dominant wave direction) or amount and species of corals at that site. As discussed above, we found that corals with branching and lobed morphologies were the most frequently observed damaged corals. Coral species with flattened morphologies (e.g. encrusting) and therefore low exposure to wave energy (e.g. mustard hill coral [*P. astreoides*] and knobby brain coral [*P. clivosa*]) dominated sites that had no damage or minor damage.

As shown above, thousands of fragments and colonies of these species have already been reattached to the reef; however, likely thousands more are still at risk. Further, in many cases, the fragments or loose colonies may have been removed completely from the reef site by the waves and are lost from the system. Thus, some sites would benefit from replanting the reef with propagated corals from nurseries to restore, or potentially enhance the protective services the reefs provide.

References

Ferrario F, Beck MW, Storlazzi CD,. Micheli F, Shepard CC., Airoldi L. 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nature Communications 5:3794.

Griffin SP, Nemeth MI, Moore TD, Gintert B. 2015. Restoration using *Acropora cervicornis* at the T/V MARGARA grounding site. Coral Reefs 34:855.

Kendall MS, Kruer CR, Buja KR, Christensen JD, Finkbeiner M, Warner RA, Monaco ME. 2001. NOAA Technical Memorandum NOS NCCOS CCMA 152 (On-line). Methods Used
to Map the Benthic Habitats of Puerto Rico and the U.S. Virgin Islands URL:
http://biogeo.nos.noaa.gov/projects/mapping/caribbean/startup.htm. Also available on U.S. National Oceanic and Atmospheric Administration. National Ocean Service, National Centers for Coastal Ocean Science Biogeography Program. 2001.

Lirman D. 2000. Fragmentation in the branching coral Acropora palmata (Lamarck): growth, survivorship, and reproduction of colonies and fragments. J Exp Mar Bio Ecol 251:41-57.

Appendix 1

Summary information for coral species in assessment surveys (transects).

Table A1.1. Number of damaged colonies, total number of colonies, damage prevalence (%), and number of fragments (Fr) for each species from transect-level surveys.

Species name	Species code	Damaged colonies	Total colonies	Damage (%)	Fr
Acropora palmata	ACR PALM	190	421	45.1	994
Branching *Porites* spp	BR POR SPP	445	942	47.2	174
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	NA
Colpophyllia natans	COL NATA	14	118	11.9	NA
Diploria clivosa	DIP CLIV	39	2784	1.4	NA
Diploria labyrinthiformis	DIP LABY	49	339	14.5	NA
Montastrea cavernosa	MON CAVE	73	1983	3.7	NA
Orbicella faveolata	ORB FAVE	139	1166	11.9	NA
Orbicella franksi	ORB FRAN	49	494	9.9	NA
Porites astreoides	POR ASTE	169	5936	2.8	NA
Pseudodiploria strigosa	PSE STRI	656	7309	9.0	NA

Table A1.2. Mean density and standard deviation (STD) of coral damage (per 100m^2) by species and number of sites where damaged species were present (n) from transect-level surveys.

Species name	Species code	Density	STD	n
Orbicella annularis	ORB ANNU	6.7	11.5	41
Branching *Porites* spp	BR POR SPP	5.7	12.4	32
Acropora prolifera	ACR PROL	3.2	2.4	3
Pseudodiploria strigosa	PSE STRI	2.5	5.0	97
Acropora cervicornis	ACR CERV	2.4	4.4	10
Dendrogyra cylindrus	DEN CYLI	2.3	5.9	18
Acropora palmata	ACR PALM	2.2	4.2	35
Siderastrea siderea	SID SIDE	2.0	5.0	55
Porites astreoides	POR ASTE	1.9	3.4	45
Orbicella faveolata	ORB FAVE	1.7	2.9	40
Montastrea cavernosa	MON CAVE	1.0	1.0	24
Diploria clivosa	DIP CLIV	0.9	1.1	17
Diploria labyrinthiformis	DIP LABY	0.9	0.9	23
Orbicella franksi	ORB FRAN	0.7	0.7	23
Colpophyllia natans	COL NATA	0.5	0.5	9

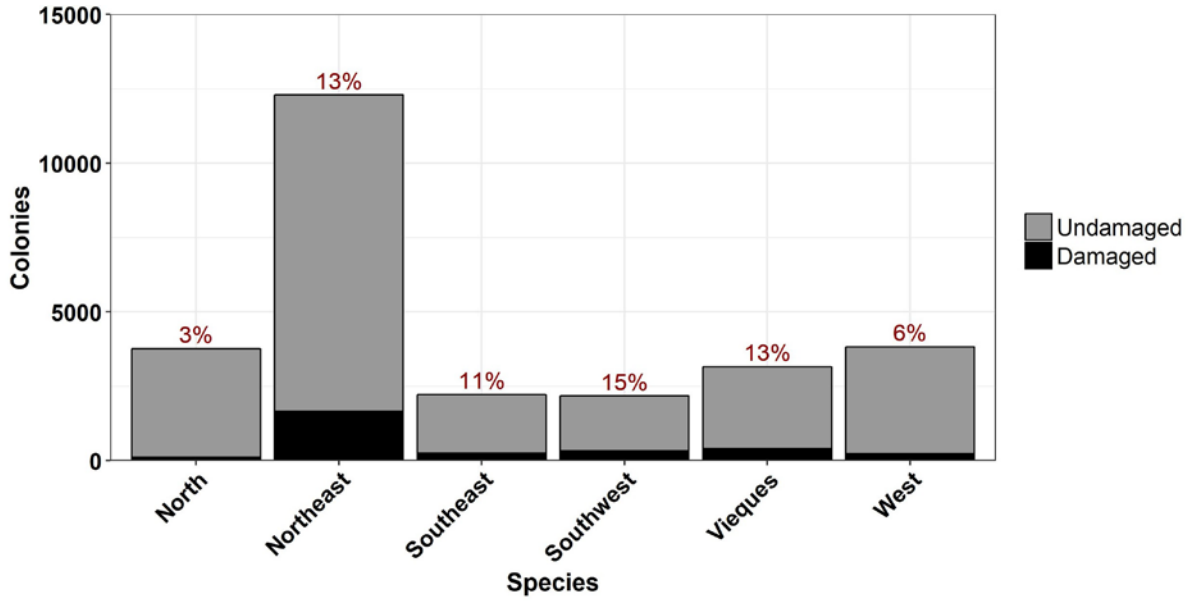

Figure A.1. Regional comparison of damaged and undamaged colonies. The northeast region had the highest number of both undamaged and damaged corals.

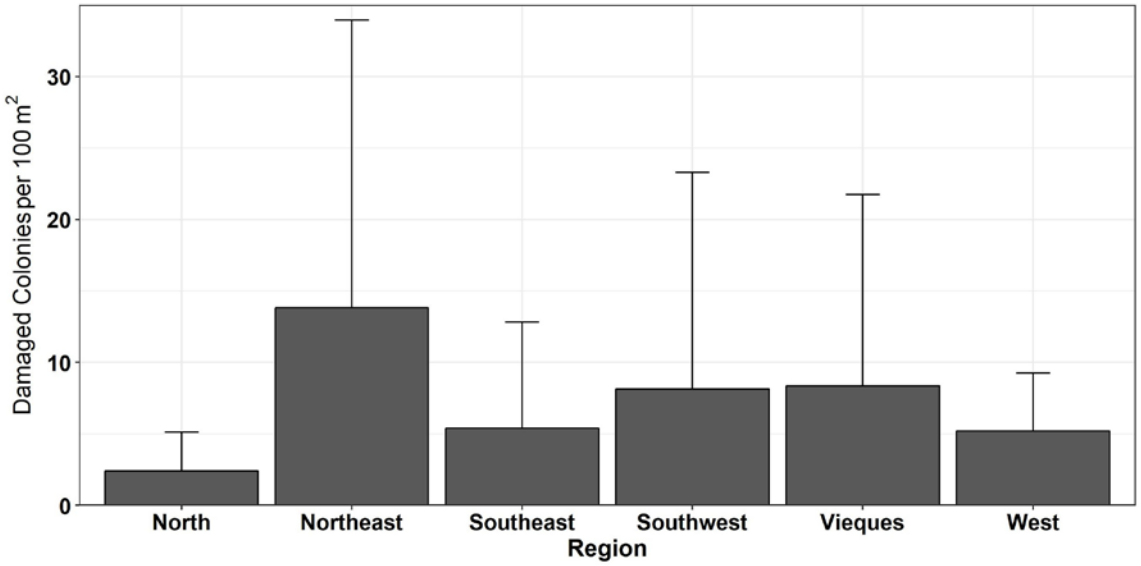

Figure A.2. Regional comparison of the density of damaged corals (colonies per 100 m^2).

Appendix 2

Summary information for coral species in roving assessment surveys of damaged areas.

Table A2.1. Prevalence of damaged colonies, total number of colonies, damage prevalence (%), and number of fragments (Fr) for each species from roving surveys.

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

Table A2.2. Mean density and standard deviation (STD) of coral damage (per 100m^2) by species and number of sites where damaged species were present (n) from roving surveys.

Species name	Species code	Density	STD	n
Pseudodiploria strigosa	PSE STRI	113	34.8	4.9
Acropora palmata	ACR PALM	58	20.2	3.4
Branching *Porites* spp	BR POR SPP	41	8.2	1.9
Orbicella annularis	ORB ANNU	56	2.5	1.3
Siderastrea siderea	SID SIDE	79	6.5	1.3
Diploria clivosa	DIP CLIV	21	4.7	1.1
Porites astreoides	POR ASTE	68	5.3	1.1
Acropora prolifera	ACR PROL	2	0.5	0.5
Acropora cervicornis	ACR CERV	9	0.3	0.3
Diploria labyrinthiformis	DIP LABY	33	0.3	0.3
Montastrea cavernosa	MON CAVE	38	0.4	0.3
Orbicella faveolata	ORB FAVE	62	0.5	0.3
Dendrogyra cylindrus	DEN CYLI	30	0.3	0.2
Orbicella franksi	ORB FRAN	30	0.3	0.2
Colpophyllia natans	COL NATA	19	0.3	0.1

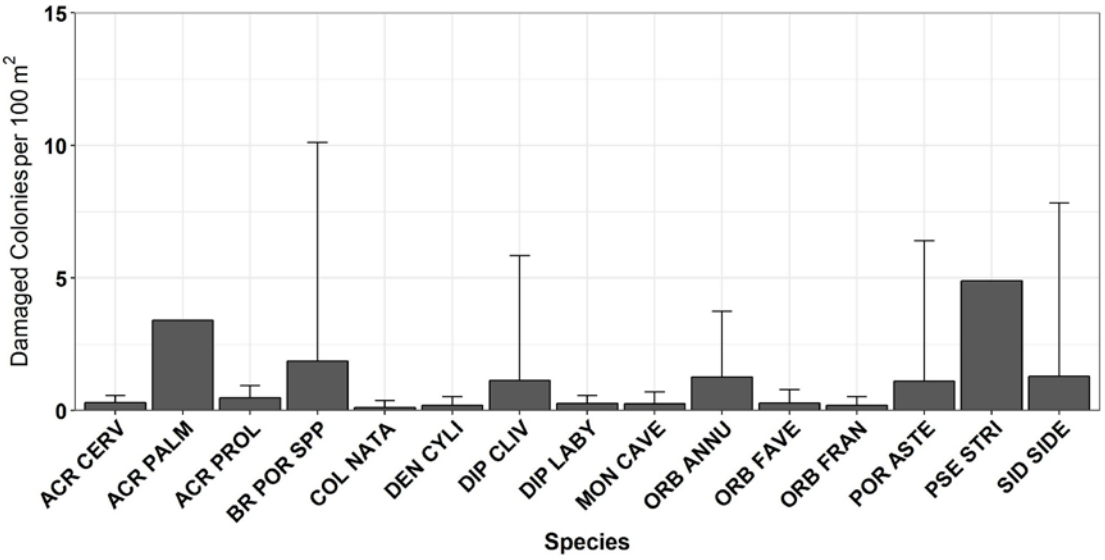

Figure A2.1. Mean density (+/- std) of coral damage by species from roving surveys.

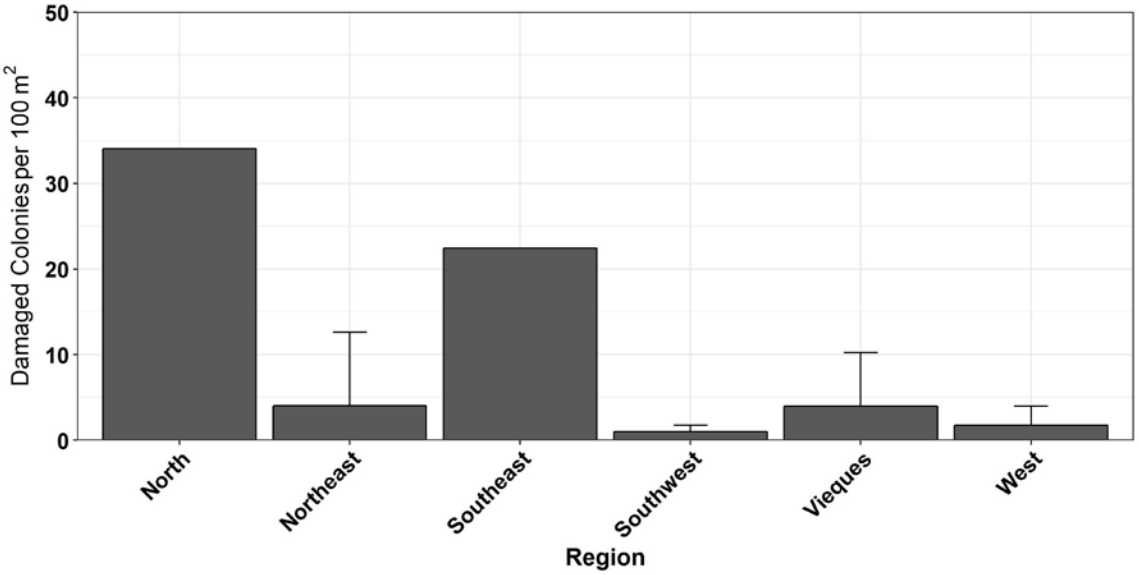

Figure A2.2. Density of coral damage by region (roving data).

Appendix 3

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

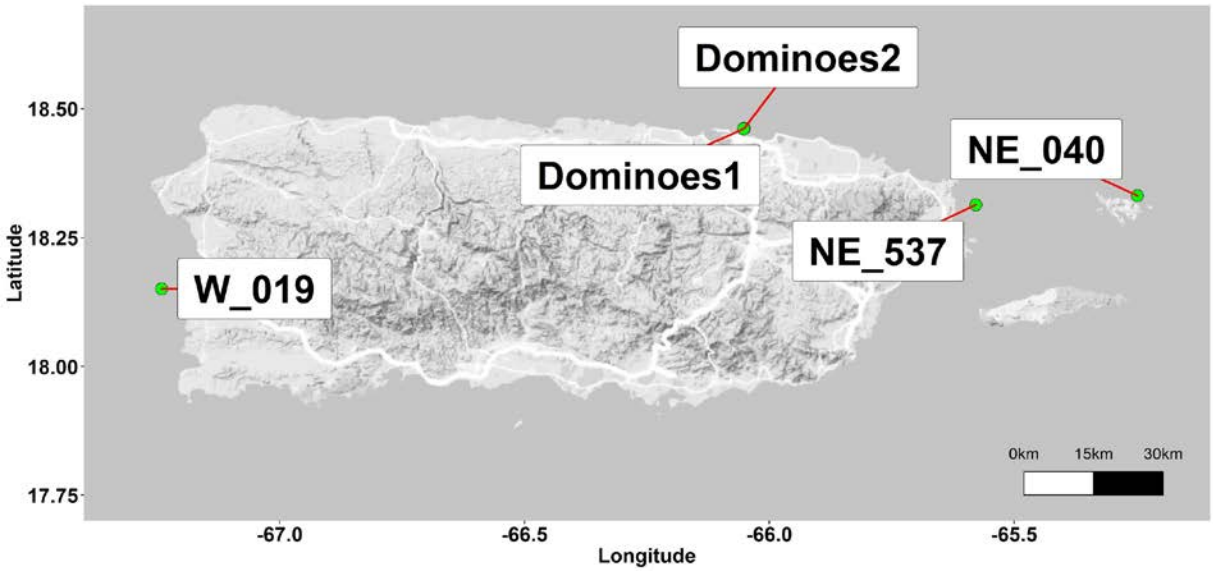

Figure A3.1. The five sites with the most severe damage to *Acropora palmata.* Summary information on the coral species damaged at each of these sites follows.

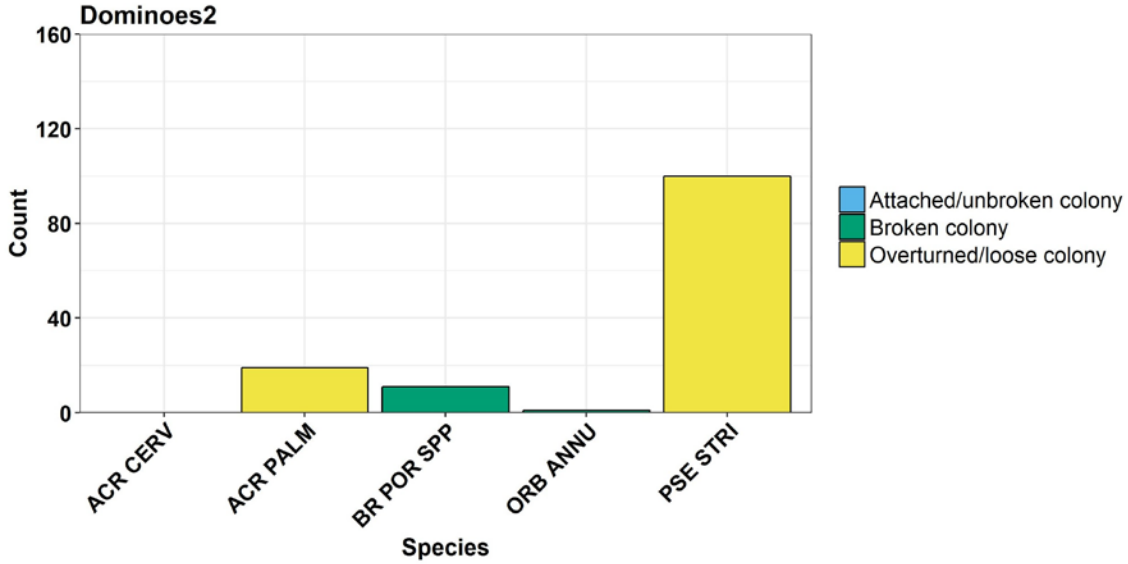

Figure A3.2. Number of damaged and undamaged colonies for all species impacted at site Dominoes2. Species impacted included *A. cervicornis*, *A. palmata,* branching *Porites* spp.*, O. annularis, P. strigosa.*

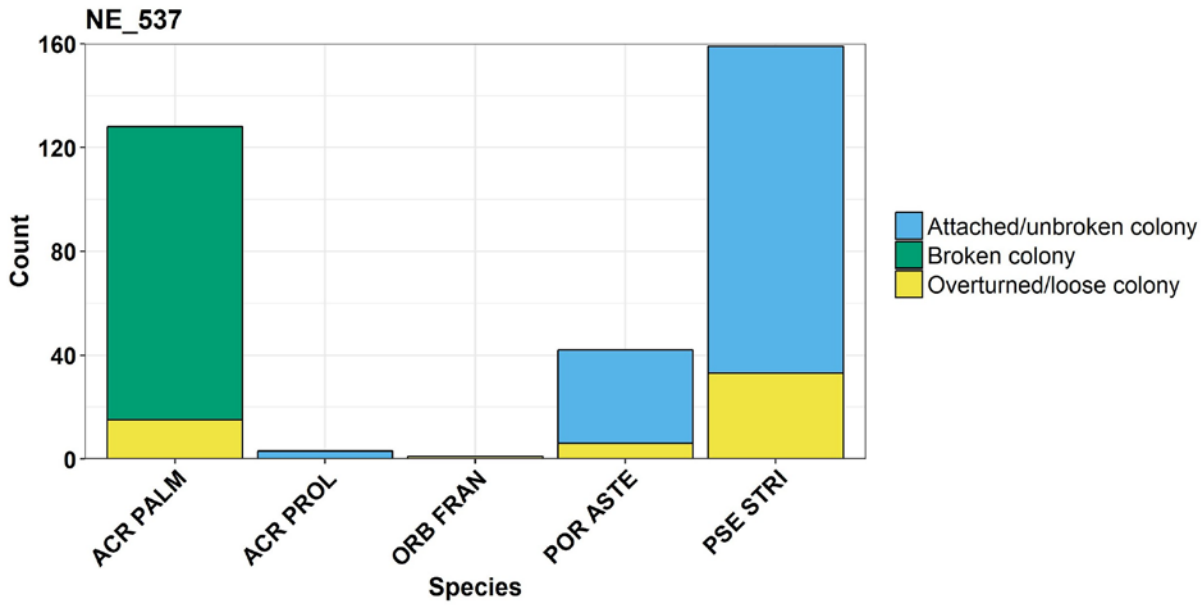

Figure A3.3. Number of damaged and undamaged colonies for all species impacted at site NE_537. Damaged species included *A. palmata, A. prolifera, O. franksi, P. astreoides, P. strigosa.*

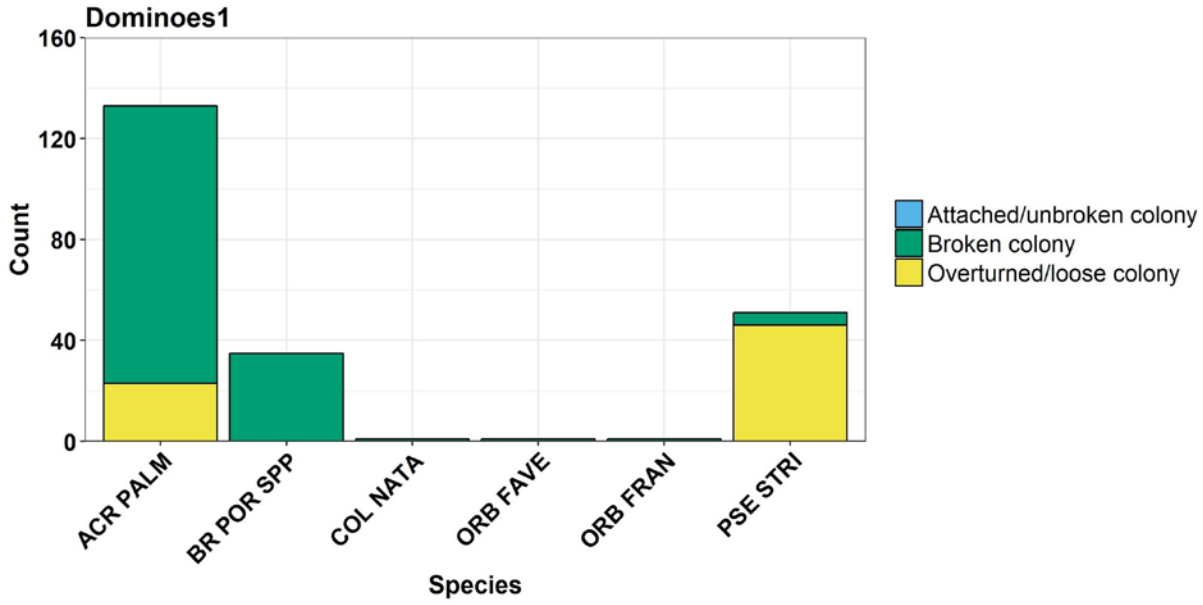

Figure A3.4. Number of damaged and undamaged colonies for all species impacted at site Dominoes1. Damaged species included *A. palmata*, Branching *Porites* spp., *C. natans, O. faveolata, O. franksi, P. strigosa.*

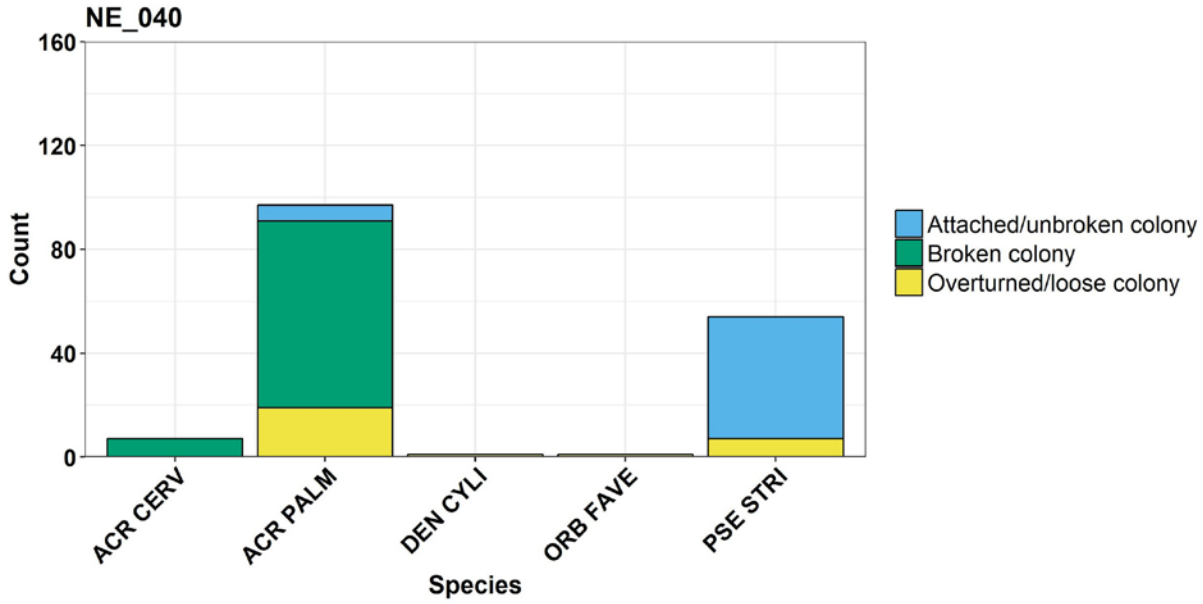

Figure A3.4. Number of damaged and undamaged colonies for all species impacted at site NE_040. Damaged species included *A. cervicornis, A. palmata*, *D. cylindrus, O. faveolata, P. strigosa.*

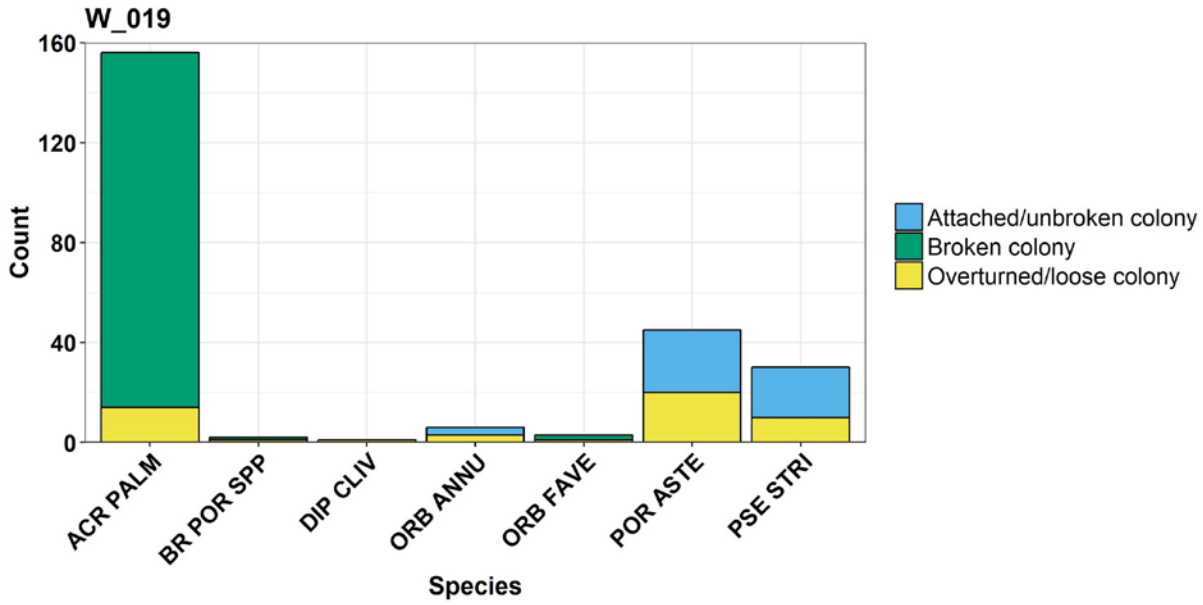

Figure A3.5. Number of damaged and undamaged colonies for all species impacted at site W_019. Damaged species included *A. palmata*, branching *Porites* spp., *D. clivosa, O. annularis, O. faveolata, P. astreoides, P. strigosa.*

Appendix 4

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

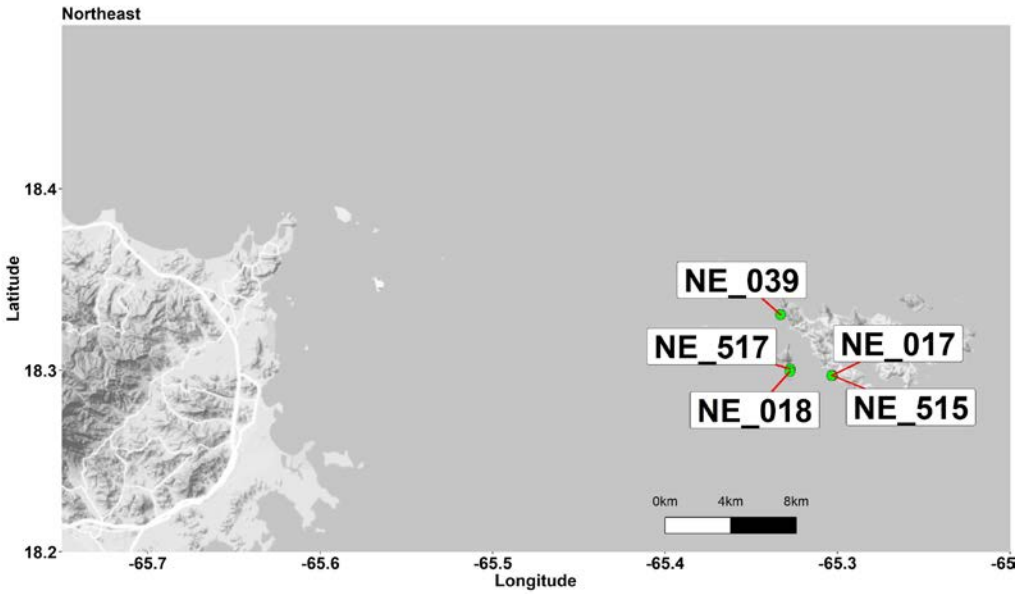

Figure A4.1. The five sites with the most severe damage to lobed star coral *Orbicella annularis.* Summary information on the coral species damaged at each of these sites follows.

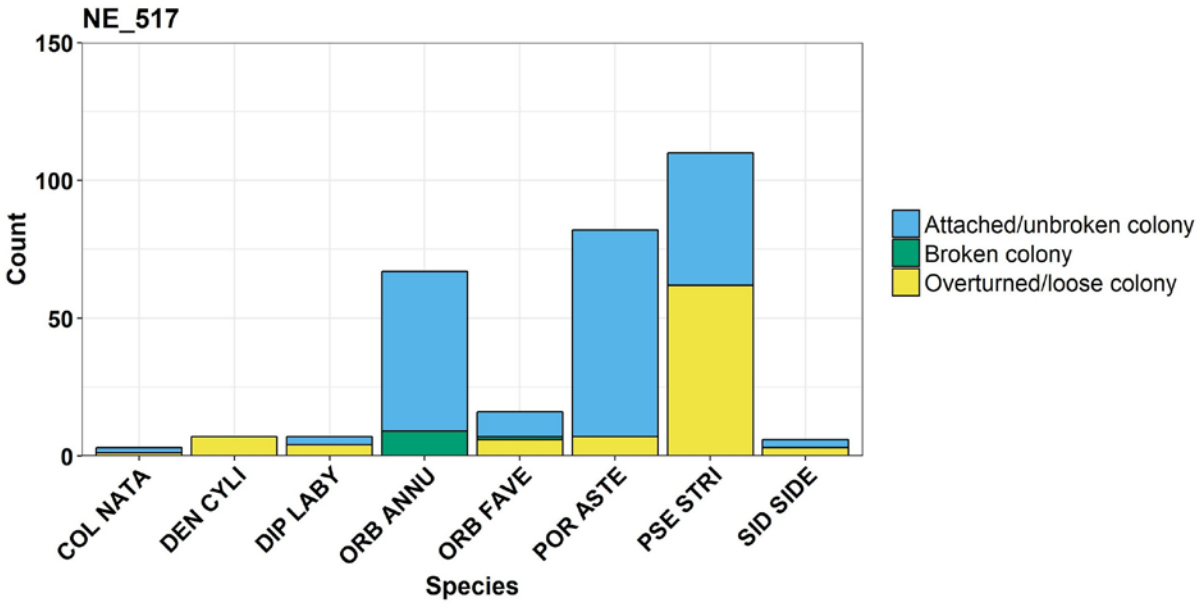

Figure A4.2. Number of damaged and undamaged colonies for all species impacted at site NE_517. Damaged species included *C. natans*, *D. cylindrus, D. labyrinthiformis, O. faveolata, P. astreoides, P. strigosa,* and *Siderastrea siderea.*

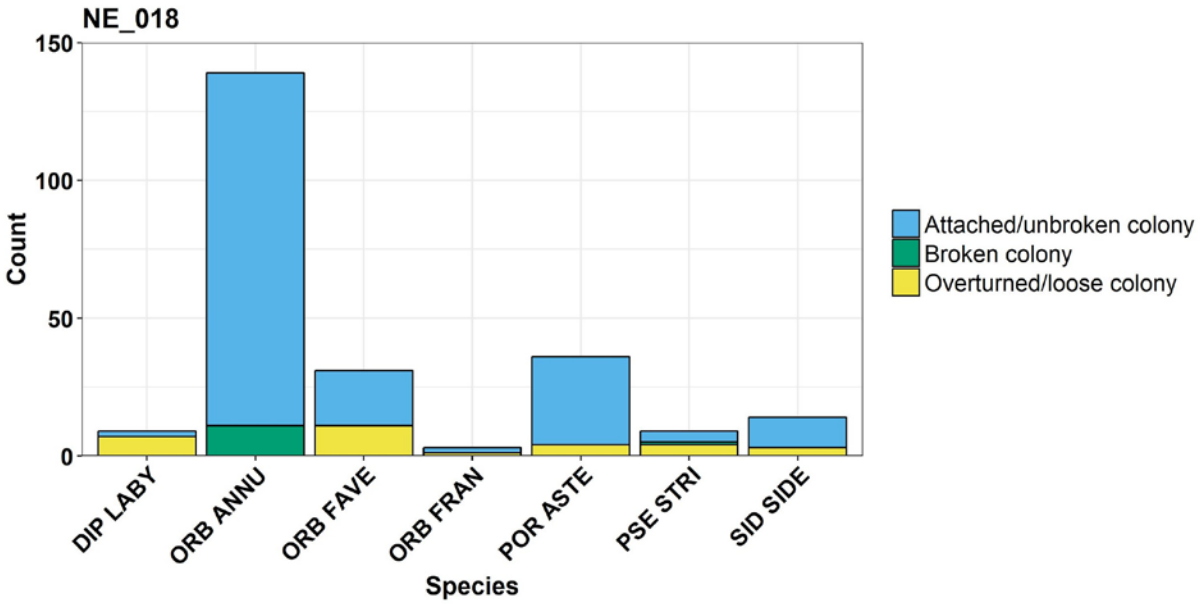

Figure A4.3. Number of damaged and undamaged colonies for all species impacted at site NE_018. Damaged species included *D. labyrinthiformis, O. annularis, O. faveolata, O. franksi, P. astreoides, P. strigosa,* and *Siderastrea siderea.*

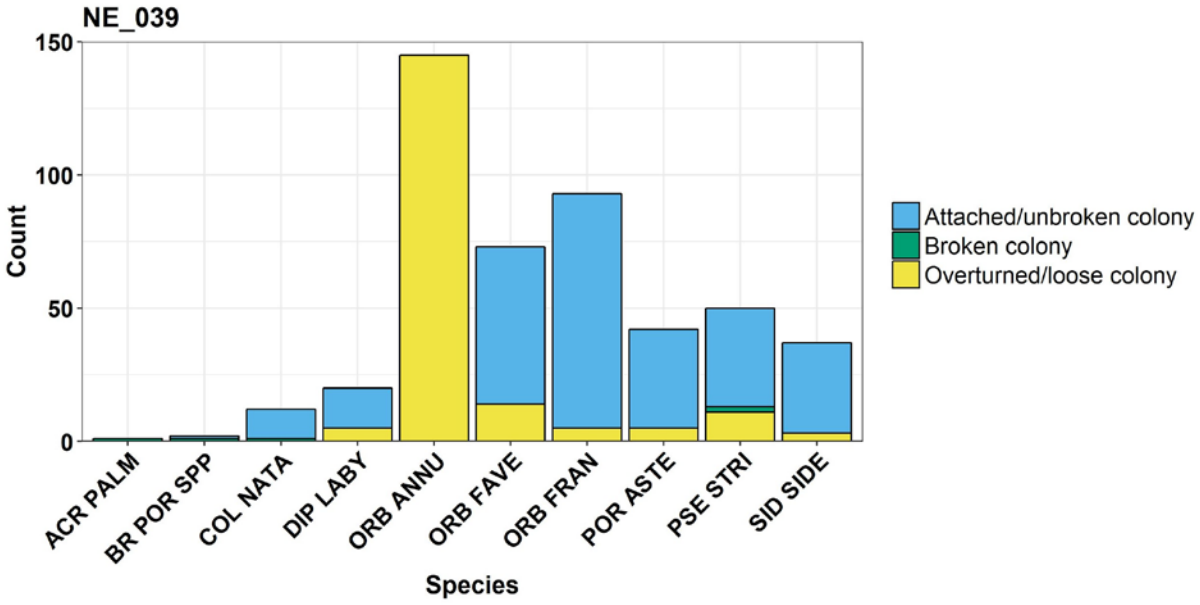

Figure A4.4. Number of damaged and undamaged colonies for all species impacted at site NE_039. Damaged species included *A. palmata,* branching *Porites* spp., *C. natans, D. labyrinthiformis, O. faveolata, O. franksi, P. astreoides, P. strigosa,* and *Siderastrea siderea.*

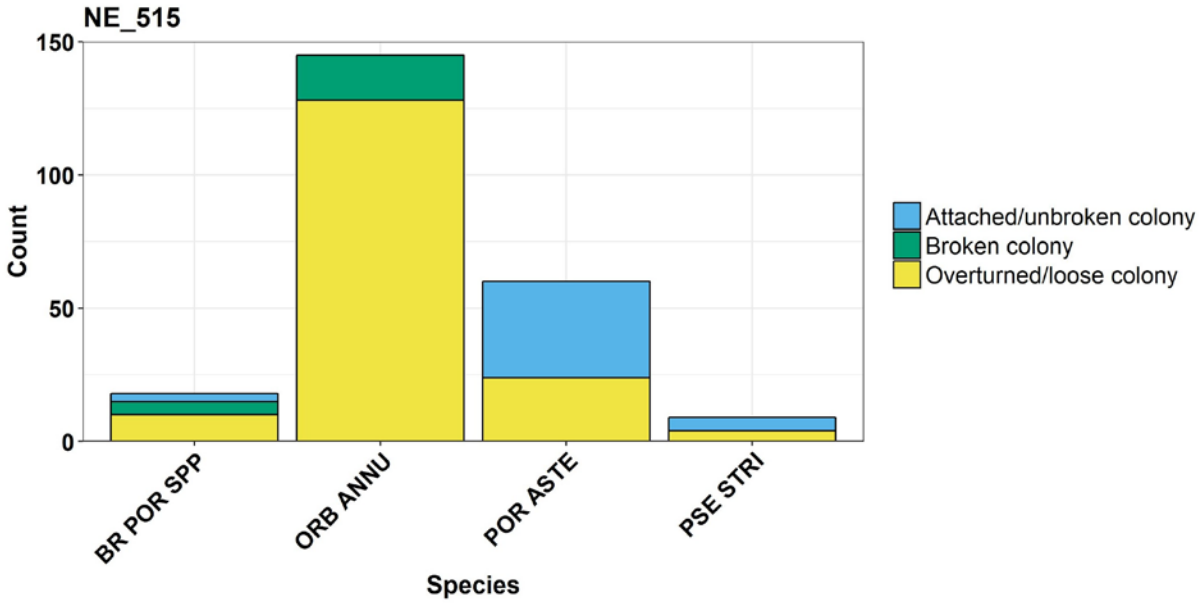

Figure A4.5. Number of damaged and undamaged colonies for all species impacted at site NE_515. Damaged species included branching *Porites* spp., *O. annularis, P. astreoides,* and *P. strigosa.*

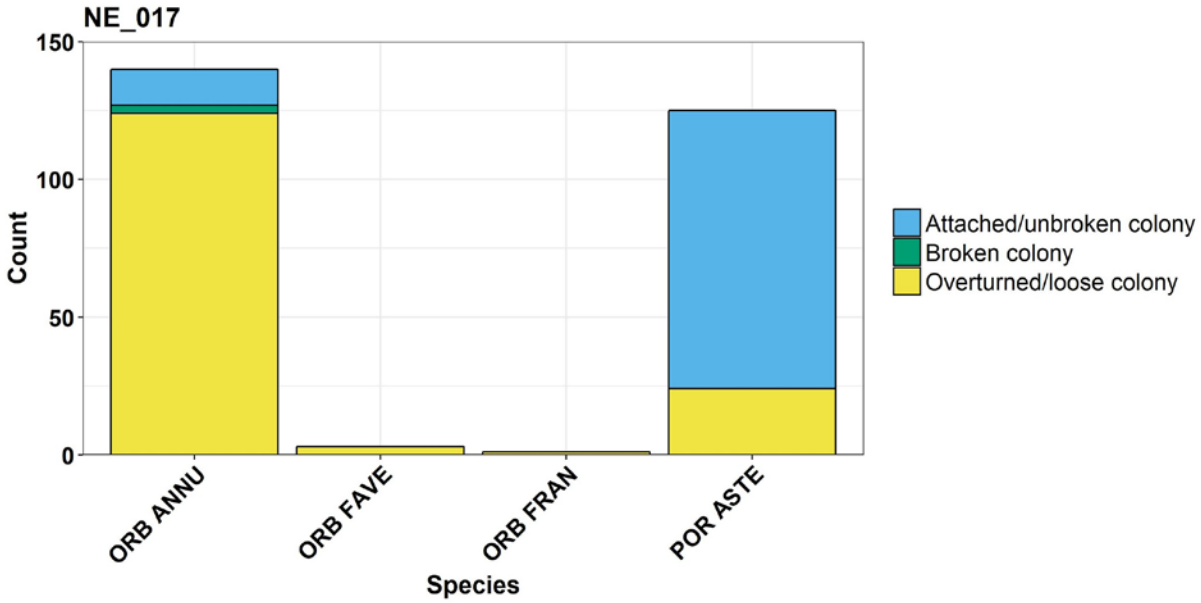

Figure A4.6. Number of damaged and undamaged colonies for all species impacted at site NE_017. Damaged species included *O. annularis, O. faveolata, O. franksi,* and *P. astreoides.*