Preliminary Assessment of Hurricane Dorian's Impact on Coral Reefs of Abaco and Grand Bahama

A report submitted to the Government of The Bahamas

by

Craig Dahlgren, PhD & Krista Sherman, PhD

On behalf of the Perry Institute for Marine Science

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Image courtesy National Oceanic and Atmospheric Administration's GOES-East

Executive Summary

Hurricane Dorian was an historic storm causing devastation to communities of Abaco, Grand Bahama and surrounding islands of the Little Bahama Bank. Using data collected from coral reefs around Abaco and Grand Bahama over the year prior to the storm, and data collected from the same reefs less than 2 months after the storm, the Perry Institute for Marine Science and its partners had an unprecedented opportunity to assess the damage from a hurricane of this magnitude across the full spatial extent of hurricane impacts. To provide a rapid assessment of reef impacts at a very coarse level, we developed a Hurricane Damage Index (HDI) based on four main types of damage – (1) physical destruction of reefs, (2) sediment movement/burial, (3) debris, and (4) coral health/bleaching. We also used Atlantic and Gulf Rapid Reef Assessment (AGRRA) data collected before and after Hurricane Dorian at 29 coral reef sites to provide a more detailed and quantitative assessment of hurricane damage to reefs across the Little Bahama Banks. AGRRA data was used to assess the effect that the storm had on key metrics of coral reef health, including:

- Structural damage to coral reefs
- Broken or dislodged coral colonies
- The amount of live coral on reefs
- The condition of coral colonies on reefs
- The amount of harmful seaweeds that compete with corals and can prevent coral growth and survival
- Fish biomass on reefs

Analysis of both the HDI and AGRRA data indicate that the damage inflicted by Hurricane Dorian to Abaco and Grand Bahama's coral reefs varied considerably in terms of the type of damage experienced by individual reefs and the severity of that damage. There was not a strong relationship between damage on land and in the sea, or between hurricane intensity and proximity and the damage observed on reefs. Instead, spatial patterns of damage likely reflect complex relationships between a variety of factors including characteristics of the reef such as, depth, proximity to land, type of adjacent marine and coastal habitats, and reef structure. Added to this complexity are factors related to Hurricane Dorian, such as its track relative to reefs, shelter of those reefs by land masses, the duration of hurricane conditions, and intensity of waves and storm surge at reefs. While some reefs were devastated, with a significant damage to corals, debris, burial in silt, bleaching and loss of fish biomass, other reefs saw little damage and may have experienced short-term benefits from Dorian through the removal of seaweeds that compete with corals.

The complex spatial pattern of damage that was observed makes overarching conclusions difficult, but several key lessons emerge from the data. Because only about 25-30% of reefs surveyed suffered severe damage, the majority of reefs may make a rapid recovery to pre-storm conditions and continue to support fisheries, tourism, and other components of Abaco and Grand Bahama's Blue Economy. Reefs that received little damage may also help to replenish many of

the severely damaged reefs. Additional management interventions are likely necessary, however, to promote recovery of damaged reefs, such as coral restoration, and protective management.

Some of the reefs that experienced severe damage were ones closest to coastal areas where debris from shore, particularly invasive Casuarina trees that were uprooted during the storm and carried by tides and the retreating storm surge across reefs. This resulted in smashed corals and destroyed reef structure. Such damage may be reduced in the future by removing these invasive species from shores and promoting natural shoreline protection.

The assessments presented in this report should be viewed as preliminary, identifying key areas to focus additional research and monitoring. We make specific recommendations for further data collection and analysis, including:

- Additional reef assessments in locations in not surveyed in this preliminary assessment.
- More focused assessments of reefs in areas where damage was greatest.
- Assessment of mangroves and seagrass systems, including habitats and key species.
- Monitoring of long-term recovery or impacts that may be ongoing (e.g., delayed coral mortality from bleaching or disease in the wake of the storm.
- Assessments of water quality, sediments, and biological sampling to determine extent of chemical pollution (e.g., petroleum), nutrients and sediments a result of the storm.
- Studies of the relationship between storm damage and measured/modeled conditions experienced by individual reefs to better understand spatial variability in damage

We also make specific management recommendations to promote the recovery of damaged marine systems, including:

- Creation of additional marine protected areas in the region to build resilience in marine ecosystems and promote recovery from storm damage and other threats.
- Removal of debris from reefs and other marine and coastal areas.
- Removal of invasive Casuarina trees from coastal areas.
- Restoration of corals to key reef areas to help “jump-start” the recovery process including use of nurseries and other propagation methods.
- Develop a rapid response protocol for responding to disasters in The Bahamas to conduct assessments of damage to marine systems and rapidly implement strategies to improve ecosystem recovery

While Hurricane Dorian’s impacts will be felt on Abaco and Grand Bahama for generations, the results of our assessments suggest that there is hope for recovery of most coral reefs in the area, which will play an important role in rebuilding communities and the blue economy of Abaco and Grand Bahama.

Overview

Hurricanes and other tropical cyclones can be major disturbances to coral reef ecosystems. Damage to reefs can include physical damage to corals resulting in corals being dislodged or fragmented through wave action or impact from debris, loss of living coral tissue through abrasion by sand, burial of corals under layers of sediment and debris, and bleaching due to changes to salinity or other stressors, such as rapid changes in temperature (e.g., Woodley et al. 1981, Edmunds and Whitman 1991, Lirman and Fong 1997). Hurricane effects on coral reefs may not all be negative, however. On healthy reefs, physical breakage of corals, particularly branching species is a means of asexual propagation where fragments can regrow colonies and contribute to reef structure, however, if the reef is not healthy, successful regrowth is likely to be compromised. Because hurricanes occur during late summer when many coral species spawn and may be under high thermal stress, hurricanes may have additional positive effects, such as mixing water to drop temperatures and relieve thermal stress during high temperature periods that may cause coral bleaching (e.g., Manzello et al. 2007). Wave action from hurricanes may also remove seaweeds from reefs, opening space for coral larvae to settle, but many studies show an increase in algae within a year of hurricanes (e.g., Rogers et al. 2001). These negative and positive hurricane effects can vary based on a combination of factors (e.g., Harmelin-Vivien 1994, Gardner et al. 2005), including:

- Strength of the hurricane
- Distance from eye of storm
- Wind speed and direction
- Wave height
- Storm surge
- Proximity of reef to land (distance and direction relative to wind and waves)
- Amount of rain produced by the storm
- Duration of hurricane impacts
- Water depth
- Land use near the reef
- Condition of reef prior to the storm and type/morphology of corals present on the reef (e.g. branching corals vs. mounding corals).

As such, the effects of hurricanes on reefs can vary considerably between storm events and even for different reefs affected by the same storm. There have been few studies, however, where reefs that have experienced different conditions by the same storm have been assessed shortly after the storm to compare damage, and even fewer studies exist where there was good data before the storm to quantitatively assess changes caused by the hurricane.

On September 1, 2019 Hurricane Dorian made landfall in Abaco. This hurricane pounded Abaco and Grand Bahama as a record-breaking major hurricane. It hit Abaco with the strongest winds ever recorded at the time of landfall for an Atlantic hurricane, having sustained winds of over 185 mph. It was also one of the slowest moving hurricanes, affecting Abaco and Grand Bahama for over two days. While the official death toll has not been released, the storm's passage left over

400 people dead or unaccounted for. Entire communities were leveled, and damage to human infrastructure was initially estimated to be more than US$7 billion. Significantly, Dorian also put catastrophic stresses on the islands' near-shore environments – especially coral reefs, seagrass beds, and mangroves – all of which are critical for local fishing industries, tourism, and protection of coastal habitat from future storms.

For the past two years, assessments of the health of Abaco and Grand Bahama's coral reefs, was a major priority for The Perry Institute for Marine Science (PIMS). From June 2018 through August 2019 PIMS led expeditions to assess the health of over 70 reefs around Abaco and Grand Bahama, including multiple sites within each national park with coral reefs and several sites that are active coral restoration sites. Assessments of reefs used several methods. The primary method used was in water diver surveys using Atlantic and Gulf Rapid Reef Assessments (AGRRA) methods. These methods have been used to assess the health of over 400 reefs around The Bahamas since 2011 (Dahlgren et al. 2014, 2016) and over 3,000 sites throughout the Caribbean region (www.agrra.org). AGRRA surveys provide quantitative information on:

- Composition of coral reef benthic communities (e.g., % cover of various organisms on the reef).
- Coral species composition, colony health (e.g., partial mortality, diseases and bleaching) and population demographics.
- Distribution and abundance of key invertebrate species.
- Distribution, abundance and size structure of key fish species.
- Human debris and environmental parameters.

Several sites around Abaco were also mapped using advanced processing high resolution photos to produce 2D orthogonal photomosaics and 3D models of reefs. Water samples and sediment samples were also collected from several of these reefs for chemical analysis and eDNA analysis prior to the storm. These samples are currently frozen will not be processed until the moratorium on exporting samples is lifted.

These data provided PIMS with an unprecedented opportunity to assess the damages caused to coral reefs by this historic storm. From October 8-22, 2019, PIMS led a team of scientists to re-survey a total of 29 reef sites, including 28 reef sites that were assessed within 15 months before Hurricane Dorian and one site that was last assessed two years prior to the storm (site 2; Fig. 1, Table 1). In addition to AGRRA data collected from all 29 sites, a Hurricane Damage Index (HDI) was developed for reef sites to provide a rapid ranking of hurricane damage at a very coarse level. Furthermore, we use photogrammetry, which consists of stitching several thousand photos of each site to construct 2D and 3D orthomosaics (currently in process) to examine changes to coral reefs over time. Water samples were also collected from most sites surveyed, and sediment samples from several sites have been stored until they can be exported for processing for future chemical and environmental DNA (eDNA) analysis. Additional qualitative observations were made on reefs in the area using a drone for sites that were not easily accessible and to better visualize damage to coastal environments over larger spatial scales.

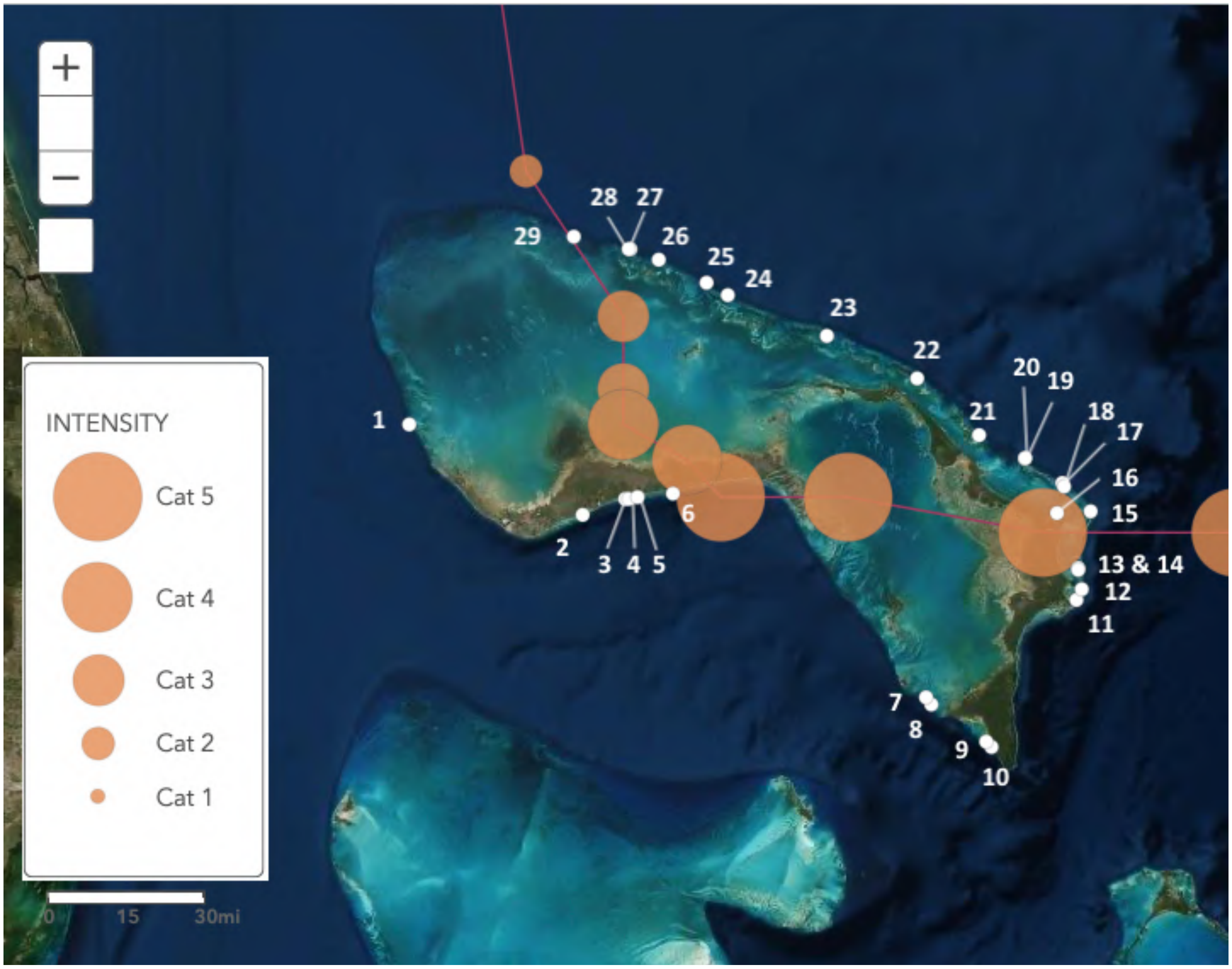


Figure 1. Coral reef sites surveyed in October 2019 across the Little Bahama Bank (white circles). Further information on each site is provided in Table 1. The track of Hurricane Dorian is shown in red with information on its intensity on the Saffir-Simpson scale at 6-hour intervals starting at noon on September 1, 2019 (far left of map) and ending at 6:00 p.m. on September 3, 2019 (top of map). Note that the only the position of the center of circulation is shown and size of tan circles indicates hurricane intensity. The extent of the wind field and wind speeds are not shown.

Methods

Based on observations at each site, damage was initially assessed using a Hurricane Damage Index ranking. We developed this index based on the type of reported hurricane damage in the literature including physical damage to corals and reef structure, debris on the reef, sediment movement and scour of corals by sediment during the storm, and bleaching, which may be due to the hurricane or may have been ongoing prior to the storm. At each of these sites, damage was ranked on a scale of 0-3 (Table 2) based on visual observations during reef surveys. Individual scores were summed to provide a Total Hurricane Damage Index for each site. This index should be considered a coarse rapid assessment of reefs affected by Hurricane Dorian, but several metrics examined in this index may be evaluated more rigorously through quantitative analysis using AGRRA data.

Details of AGRRA methods are available at www.AGRRA.org. Briefly coral reef benthic communities were quantitatively assessed using point intercept surveys of what was growing on the sea floor at 10 cm intervals along 10 m transects (n = 4-6 per site). Benthic surveys also included counts of key mobile invertebrate species (urchins, lobster, conch and sea cucumbers) within 10 x 1 m belt transects, and surveys of coral recruits and substratum classification within 25 cm x 2 5cm quadrats at 2 m intervals along each transect (n = 5 per transect). Coral surveys included identification, measurement (length, width, height), assessment of living tissue and partial mortality as well as assessments of disease and bleaching for each colony within a 10 x 1 m belt transect (n = 2 per site). Fish surveys included the identification, count and size estimation of 70 fish species within 30 x 2 m belt transects (n = 6-12 per site).

Table 1. Summary of data collected from each site before and after Hurricane Dorian. Dates listed pre-Dorian assessments are for the collection of AGRRA benthic, coral and fish data. Photo indicates the availability of photomosaic data. For pre- Dorian surveys, photo data was collected between April 2019 and June 2019.

Site No.	AGRRA Code	Depth (m)	Pre Dorian							Post Dorian						
			Date	No. Benthic Transects	No. Corals	No. Fish transects	Water sample	Sediment sample	Photo	Date	No. Benthic Transects	No. Corals	No. Fish transects	Water sample	Sediment sample	Photo
1	WGB007	15	7/3/19	5	109	10	X	X		22-10-19	6	152	5	X	X	X
2	PCNP002	4	08/16/16	3	41	6				09-10-19	5	121	5			X
3	GB003	5	11/14/18	6	186	8				09-10-19	5	122	7			X
4	GB007	10	11/14/18	6	178	7				09-10-19	5	130	7	X		X
5	GB012	11	11/15/18	6	134	7				10-10-19	6	135	7	X		X
6	GB010	12	11/15/18	6	109	8				10-10-19	6	153	6	X		X
7	AB101	4	11/11/18	5	199	5			X	11-10-19	5	125	4	X		X
8	AB016	4	11/11/18	6	218	6			X	11-10-19	6	142	6	X		X
9	AB021	9	11/12/18	6	226	7				12-10-19	6	154	6			X
10	AB019	14	11/12/18	6	224	7				12-10-19	5	190	7			X
11	AB212	6	5/31/19	6	50	6		X		16-10-19	6	95	7	X		X
12	AB213	7	5/31/19	6	74	7		X		16-10-19	6	116	7			X
13	AB200A	7	5/26/19	4	55	7		X	X	15-10-19	6	85	7	X	X	X
14	AB200B	3	5/26/19	4	42	8		X	X	16-10-19	6	80	7	X		X
15	AB211	8	5/30/19	6	56	6		X		16-10-19	6	129	7	X		X
16	AB201	2.3	1/24/19	5	51	3			X	15-10-19	6	39	3	X		X
18	AB203	14	5/27/19	6	105	10		X		17-10-19	5	149	6	X	X	X
19	AB207	13	5/29/19	6	59	7		X		17-10-19	4	107	5			X
20	AB206	6	5/29/19	6	42	6		X		17-10-19	6	166	6	X	X	X
21	AB210	5	5/30/19	6	69	8		X		17-10-19	6	91	6			X
21	AB220	10	6/28/19	6	34	7	X	X		18-10-19	6	141	7	X		X
22	AB222	5	6/29/19	5	115	9	X	X		18-10-19	6	125	7	X		X
23	AB217	3	6/27/19	6	52	9	X	X		18-10-19	6	147	7	X	X	X
24	AB226	10	6/30/19	6	141	8	X	X		20-10-19	6	232	6	X	X	X
25	AB215	5	6/27/19	6	54	10	X	X		21-10-19	3	115	5			X
26	AB214	5	6/27/19	5	79	11	X	X		21-10-19	3	154	7	X	X	X
27	AB231	7	7/2/19	6	125	9	X	X		20-10-19	6	162	6			X
28	AB228	8	7/1/19	6	147	10	X	X		20-10-19	6	170	6	X	X	X
29	AB230	8	7/1/19	4	106	6	X	X		22-10-19	6	150	6	X		X

In this report, we present the quantitative results from AGRRA surveys for metrics closely associated with hurricane effects, including:

- Physical damage to corals and reef structure

- Changes in benthic communities
- Coral bleaching
- Changes in fish biomass

All AGRRA and Hurricane Damage Index results are presented spatially in graphic form to provide a simple way to assess and visualize geographic patterns. Other quantitative measurements (e.g., temperature records) and qualitative observations (visual, photogrammetry, and drone observations) are also discussed. Results and discussion of other data collected (e. g., water samples, eDNA, photogrammetry) will be presented when analyses are completed.

Table 2. Scoring for each component metric for the Hurricane Damage Index. It should be noted that this is a qualitative scoring system based on observations at the site by members of the survey team.

Score	Damage	Debris	Sediment	Bleaching
0	No dislodged/ broken corals	No debris visible	No sediment movement or scour visible	No pale/ bleached corals
1	Small corals dislodged/ broken	Small amounts of terrestrial debris: leaves, small pieces trash	Some evidence of minor sand scour	Some pale/partial bleached corals
2	Larger corals dislodged/ broken	Branches/ plastics/ light metal	Light siltation; sediment moved to/from base of reef	Many pale/partial bleached corals
3	Major structural damage to reef	Large trees/trash	Heavy siltation/ large silt & mud deposits	Widespread bleaching (may not be all species)

Hurricane Damage Index

This qualitative index is the coarsest measure of impacts to reefs and the most subjective, but it provides an overall view of reefs that may supplement more qualitative indices of hurricane impacts in subsequent sections. Despite its coarse and subjective nature, we feel it is a good tool for rapidly categorizing storm damage. In Figure 2. we show the assigned score for each category of reef damage at each site. The composite Hurricane Damage Index score, a sum on individual indicators for each site, is shown in Figure 3. Based on this index, the greatest levels of damage generally occurred at sites closest to the path of the storm, and sites that may have been in the lee of land away from the central track of the storm received little damage. There was quite a bit of variability in scores, however. For example, Site 1 off West End Grand Bahama had one of the highest HDI scores despite being farthest from the track of the storm but sites 15 and 29, which were close to the eye of the storm as it made its first landfall and exit from The Bahamas, had some of the least damage. Complex interactions between the location of reefs, depth, reef structure, distance and direction from the eye of the storm, fetch and shelter from land, as well as proximity to sources of debris and sediment played a role in determining damage. Although HDI is a useful tool for rapidly assessing reef damage, greater insights can be gained from quantitative assessments of reef conditions based on AGRRA surveys as presented in the following sections.

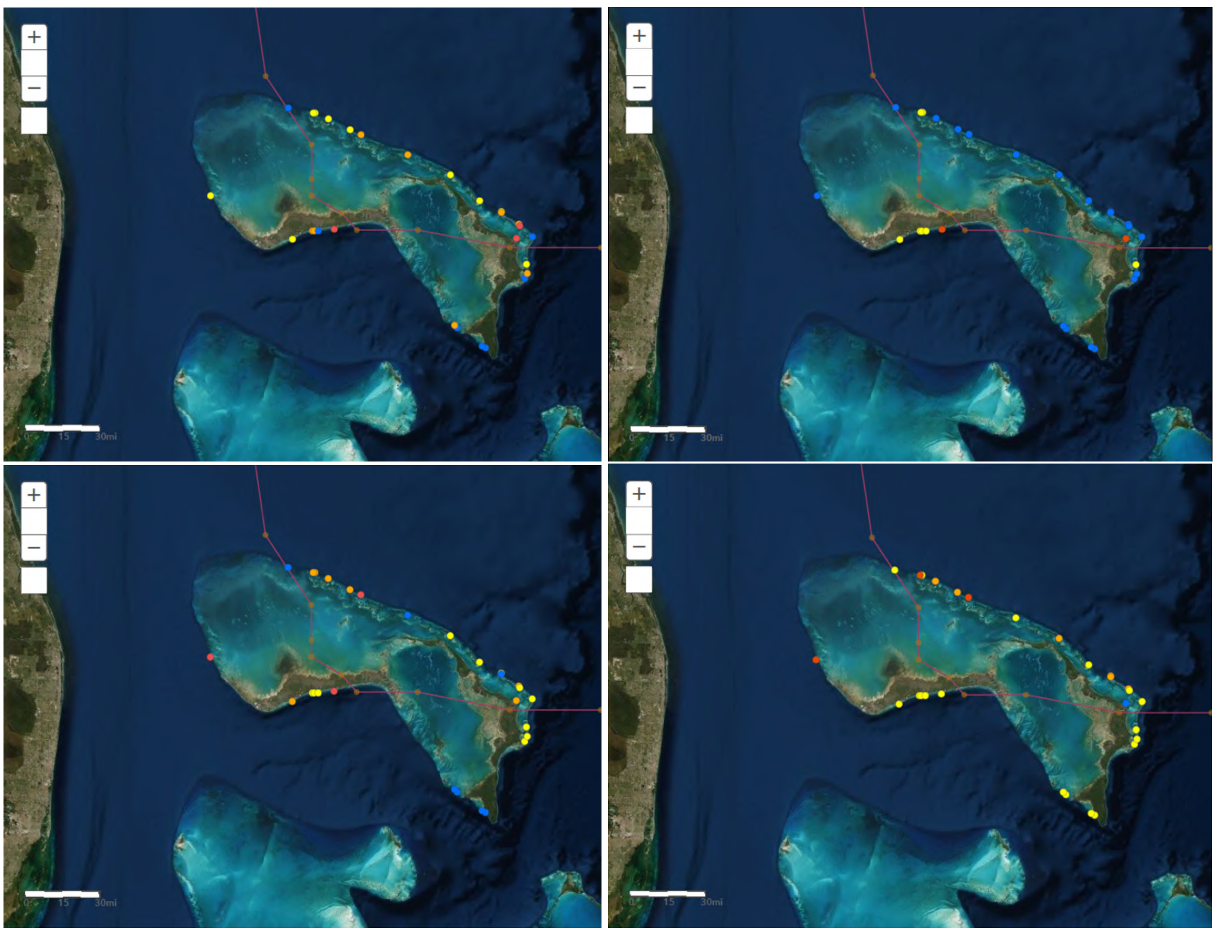


Figure 2. Components of the Hurricane Damage Index including (clockwise from top left) (1) physical damage to reefs and corals; (2) natural and anthropogenic debris; (3) coral bleaching; and (4) sediment disturbance and burial. Site rankings followed the description of rankings in Table 2 with sites receiving a score of 0 = blue; 1 = yellow; 2 = orange; and 3 = red. Hurricane Dorian's track is shown as a red line with progression of the storm marked in 6 hour increments following Figure 1.

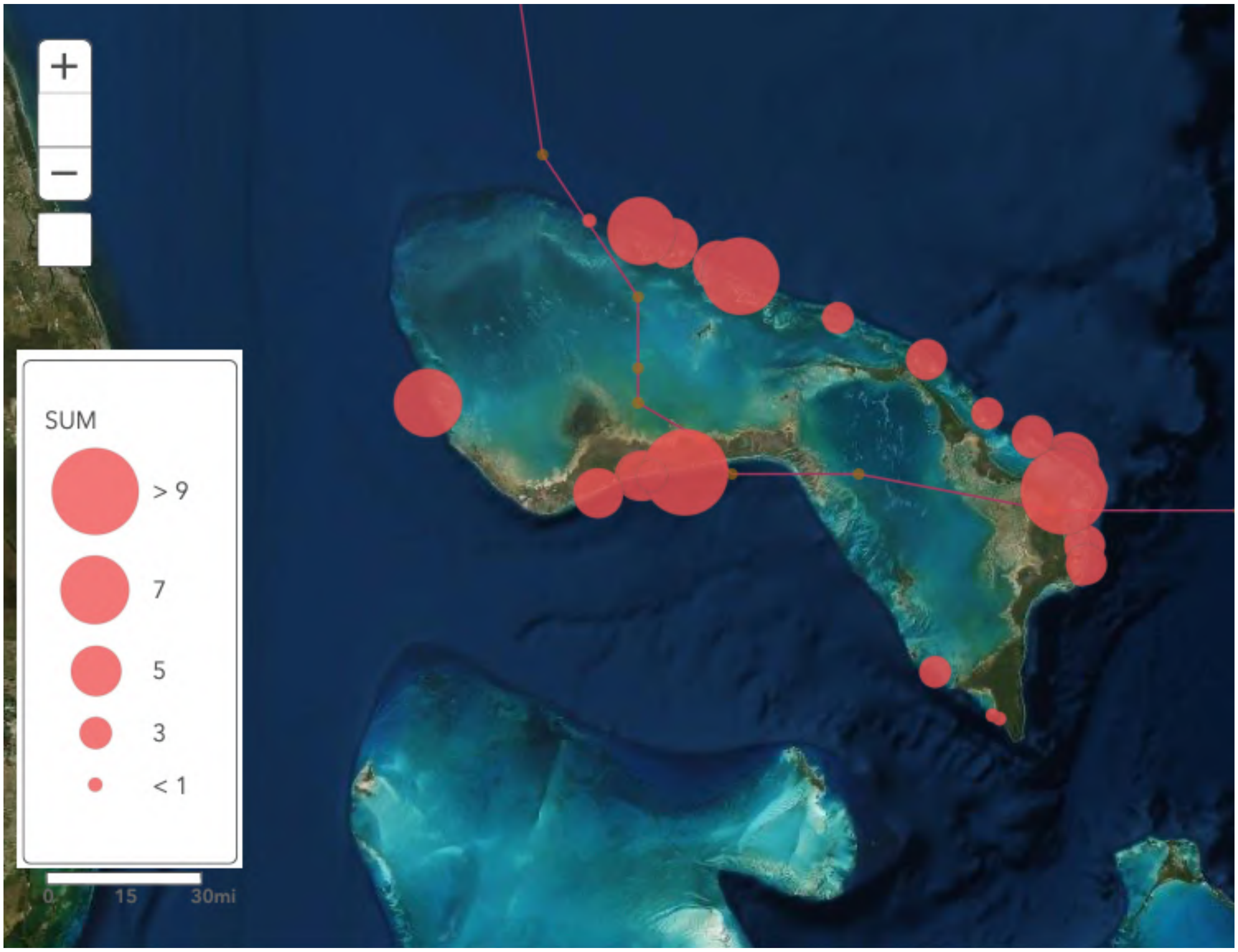


Figure 3. Composite Hurricane Damage Index scoring calculated by summing individual scores for each metric at each site. Hurricane Dorian's track is shown as a red line with progression of the storm marked in 6-hour increments following Figure 1.

Damage to Corals and Reef Structure

Perhaps the greatest damage to reefs as a result of a hurricane is the physical destruction to reef structure. During AGRRA surveys, we quantitatively assessed two components of structural damage to coral reefs. The first component included changes to the structural complexity of reefs as measured in the maximum vertical relief (measured in cm) of the reef in 1 m x 1 m area at 5 m intervals along 30 m long transects (during AGRRA fish surveys). For each site, the mean vertical relief in transects was compared before and after Hurricane Dorian. Changes were compared using an analysis of variance (ANOVA) model on untransformed data. To best depict the spatial variability in hurricane impacts, we have plotted the results on a satellite image of the area, similar to the area for each metric, using color coding to indicate a significant negative effect, positive effect or no change in the metric.

Significant changes on reef structural complexity ($p < 0.05$) was detected for two sites: Mermaid Reef, a shallow reef off Marsh Harbour (Site 16) composed of large mountainous star coral, *Orbicella faveolata*, colonies, and Moraine Cay Reef (23) in the northern Abaco barrier reef, which was largely comprised of elkhorn coral, *Acropora palmata* (Fig. 4). Both sites showed a decrease in structural complexity of the reef. In the case of Moraine Cay Reef, the reduction in structural complexity was the result of breakage to relatively fragile branching *A. palmata* colonies that dominated the reef crest. At Mermaid Reef, large boulders forming the reef structure were broken up and/or moved over tens of meters on the seafloor and scattered across a large area. Many of these colonies were up to 2 m in diameter and over 1 m in height.

As part of an in-depth long-term study of Mermaid Reef prior to hurricane Dorian, we constructed a 35 m X 35 m 2D orthomosaic and 3D computer model of the reef from over 6,000 high resolution underwater photographs of the reef taken in April 2019. In October 2019, we re-photographed the same reef area to construct similar 2D and 3D products. While water clarity and other technical issues have delayed the completion of final post-storm orthomosaics and 3D models of Mermaid Reef, we have included the pre-Dorian orthomosaic and a preliminary version of the post-Dorian orthomosaic for comparison (Fig. 5). These images provide further illustration of structural changes to Mermaid Reef that occurred because of the storm as well as debris.

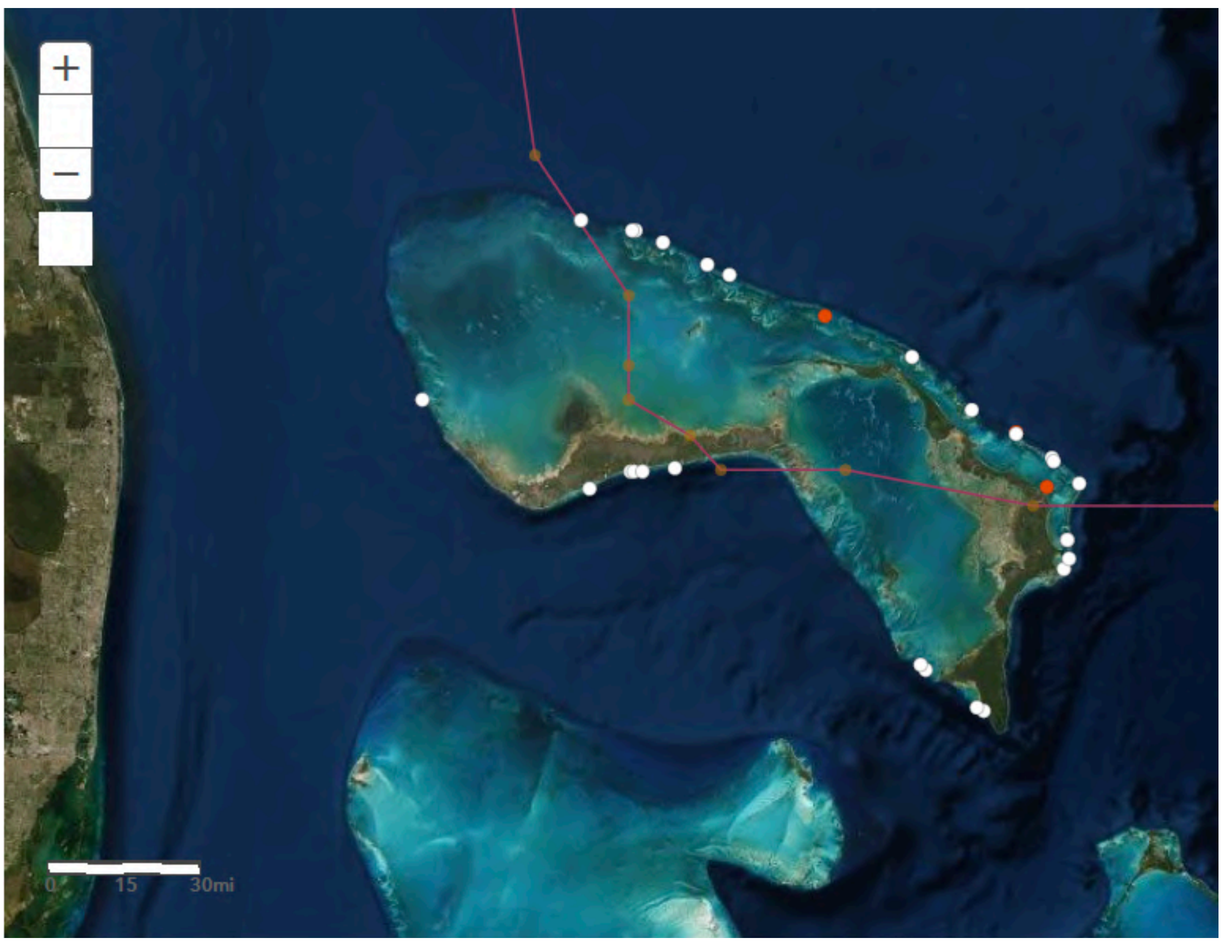


Figure 4. Comparison of reef structure before and after Hurricane Dorian. Sites marked in white are ones where no significant changes were detected, sites marked in red were ones where the reef saw a decrease in structural complexity.

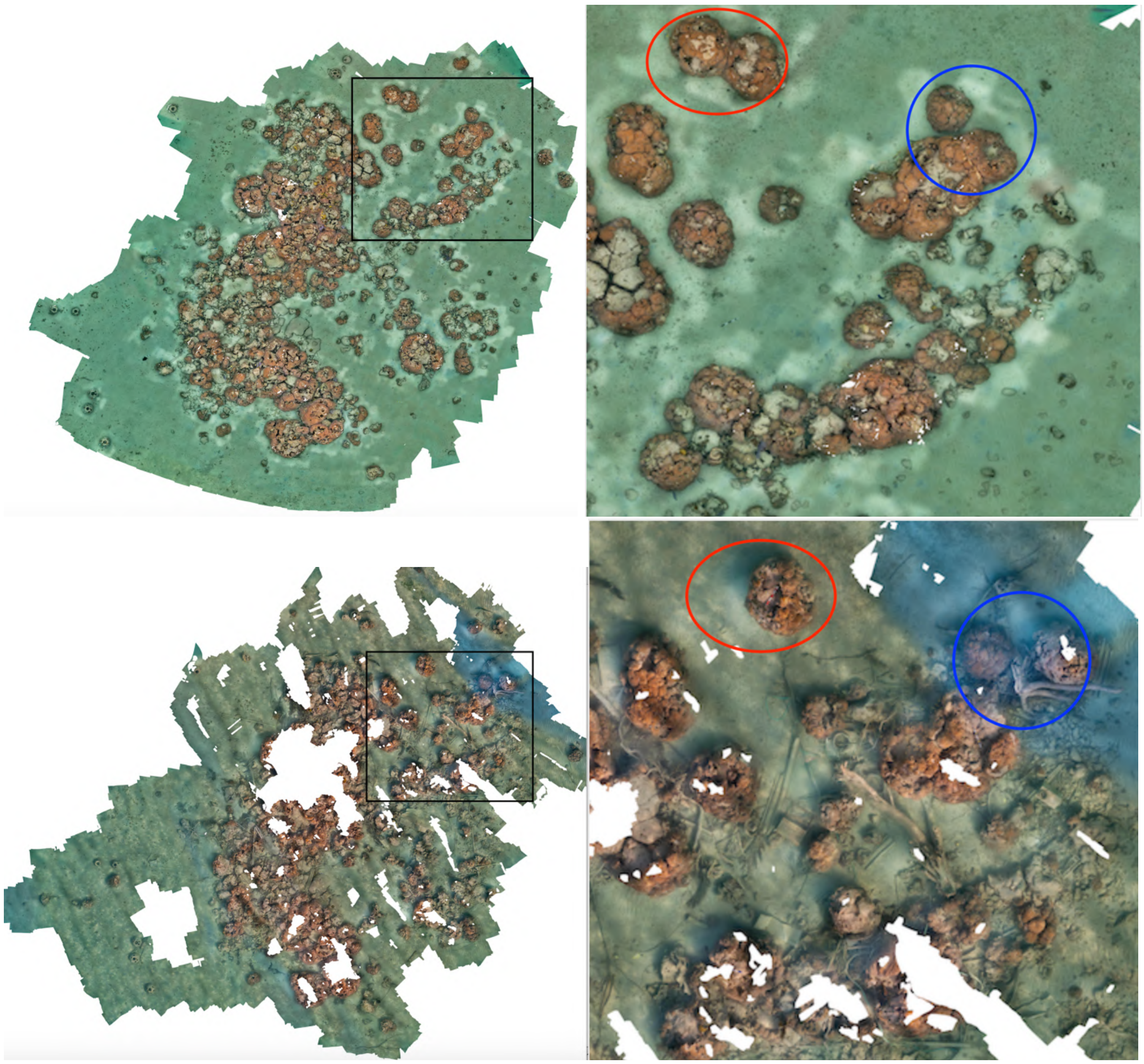


Figure 5. Pre-Dorian (top) orthomosaic image (from photographs taken in April 2019) and after-Dorian (bottom) orthomosaic images (October 2019) of Mermaid Reef (Site 16). The post-Dorian orthomosaic is preliminary and still being processed to fill in gaps. Left side images are whole reef images (approximately 35 m x 35 m) with a box outlined to show the location of the zoomed in portion of the reef depicted in the images to the right. Images on the right side provide a closer view of a section of the reef before and after, showing the extent of debris (natural and anthropogenic) as well as the movement of coral colonies and changes to reef structure. Specific areas of reef where large colonies >1 m in diameter were moved are circled in red and blue for comparison.

In addition to changes in the structural complexity of reefs, damage to reef structure was measured on a finer scale by examining the amount of breakage or fragmentation of coral colonies. During AGRRA surveys, counts were made of the number of loose coral fragments and the percent of coral fragments observed were compared for each site before and after Hurricane Dorian using a G-test. Before the storm, the percent of corals observed that were loose fragments varied among sites from 0-4% of colonies surveyed. After Hurricane Dorian, approximately one third of the sites surveyed had significant increases in the percent of fragmented corals ($p < 0.05$; Fig. 6). In most cases, the percentage of corals fragmented at a site increased by 5% or less, but the number of fragments at Moraine Cay Reef (Site 23) increased to 9% and Mermaid Reef (Site 16) increased to 23% of all corals. At several sites, the majority of coral fragments were branching species, particularly critically endangered elkhorn coral (*A. palmata*) and staghorn coral (*A. cervicornis*), but there were also broken pieces of finger coral (*Porites* spp.), as well as plating (e.g., *Agaricia* spp.) and massive corals (e.g. *Orbicella* spp.).

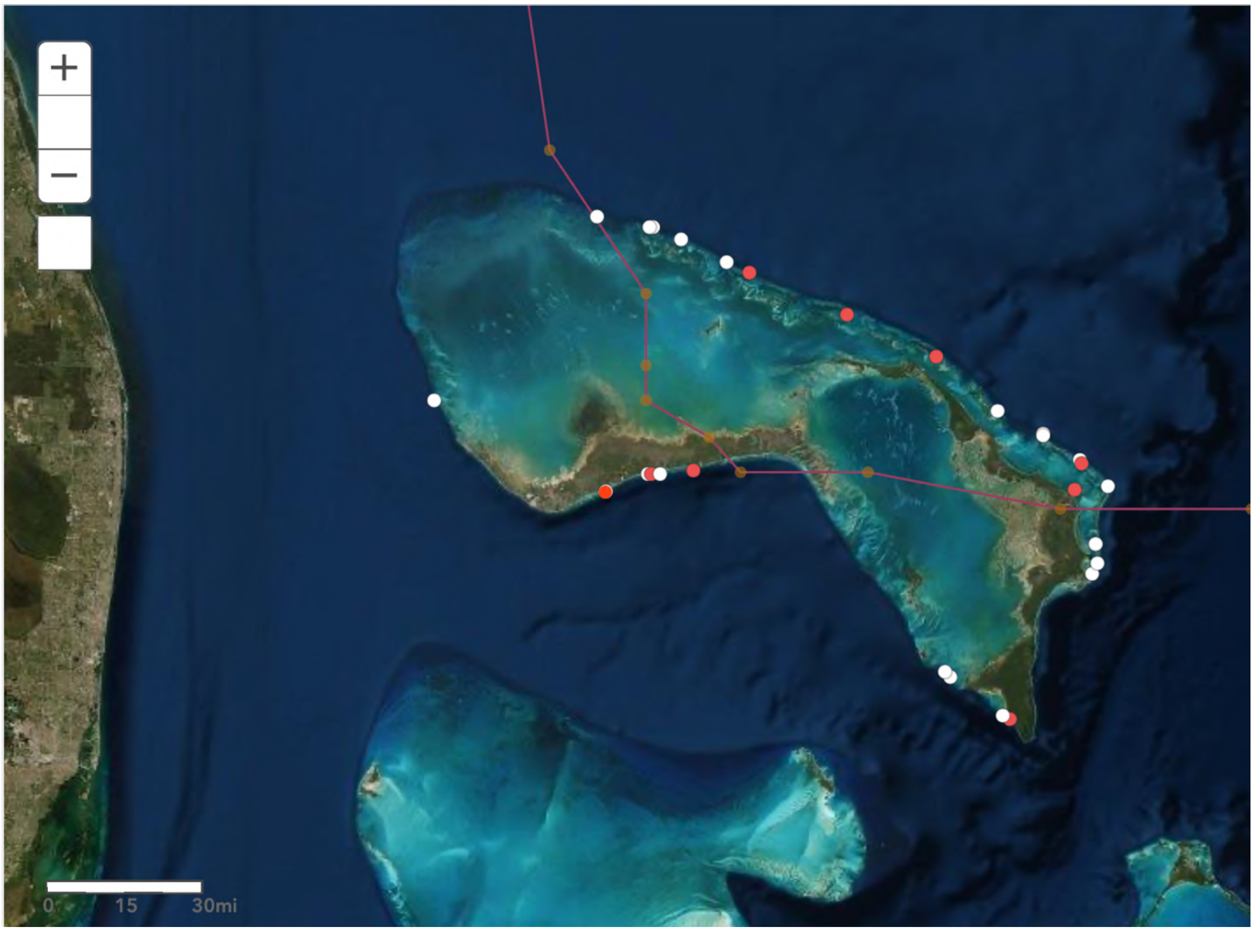


Figure 6. Comparison the percentage of corals observed that were fragments before and after Hurricane Dorian. Sites marked in white are ones where no significant changes were detected and an increase in the percentage of coral fragments is shown in red.

The structural damage to reefs is of particular concern because reduced structural complexity decreases habitat diversity for organisms living on reefs, including both fish and invertebrate species. While broken coral fragments may survive and regrow on the reef, most of fragments observed had been damaged by physical contact with the sea floor, debris, or were partly buried in the sand. Survival probability for many fragments would be improved by reattaching them to the seafloor or parent colony using epoxy, cement, or other restraint, however, an examination of many fragments or large pieces of reef that had been moved showed severe damage to living coral tissue by the time of our surveys. Restoration efforts to secure loose fragments and to harvest live portions of severely damaged colonies for propagation in either *in situ* nurseries or *ex situ* facilities for the purpose of reintroducing colonies to damaged reefs may greatly increase the recovery of reefs.

Hurricane Impacts to Reef Building Corals

In addition to breaking corals and damaging reef structure, hurricanes can decrease the overall amount of live coral on a reef and the health of coral colonies by increasing various stressors such as siltation, changes in temperature, salinity, and pollution (debris and chemical pollution) washed in to the sea from land. AGRRA benthic point intercept surveys provide information on the percent cover of key components of benthic communities including percent cover of live coral. We examined the change in the percent cover of live coral on a site by site basis by comparing the amount of live coral cover in multiple replicate transects before and after Hurricane Dorian using a non-parametric Mann-Whitney U test.

There was little measured change in percent coral cover across sites. Only two sites (Site 19: $p = 0.01$; Site 28: $p = 0.026$) had significant changes in the amount of living coral on transects, both of which had a decrease in live coral cover. Many other sites also saw a decrease in mean coral cover from before to after the storm, but these decreases were not significant due to high variability in live coral cover among transects, and low live coral cover both before and after the hurricane. In the case of Mermaid Reef off Marsh Harbour (Site 16), the decrease in coral cover from 50% live coral cover to 43% live coral was not significant, but loss of coral cover may have been underestimated since transect surveys were limited to reef areas, but the total reef area decreased due to structural damage to the reef (discussed previously).

Coral bleaching was also noted at many sites surveyed in October 2019. Mass bleaching events have been noted fairly regularly off Abaco and/or Grand Bahama during the summer and early autumn over the past decade, with major events last occurring in 2015 and 2016. Because these bleaching events are seasonal and vary annually, no statistical comparisons were made between pre- and post-Dorian assessments, but spatial bleaching patterns in October 2019 are presented here to indicate where corals were most affected by bleaching.

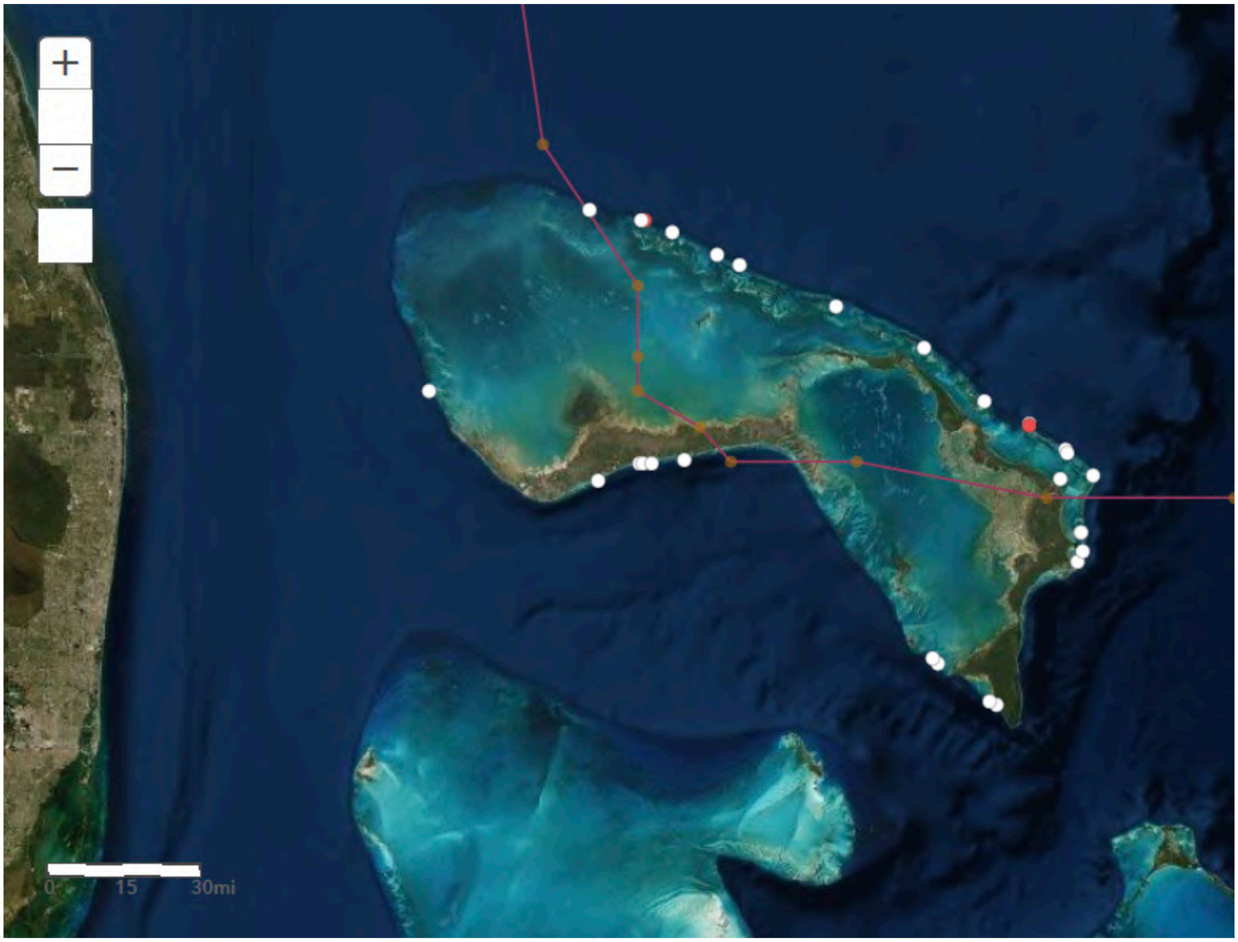


Figure 7. Comparison of percent cover of live corals before and after Hurricane Dorian. Sites marked in white are ones where no significant changes were detected and sites marked in red were ones where the there was a significant a decrease in live coral cover.

With field surveys alone, we cannot determine the cause of bleaching, but the likely cause is temperature stress. While high water temperatures leading to bleaching may have been occurring prior to Hurricane to Dorian, storm-related stresses are likely to have contributed. There are several lines of indirect evidence to support this assertion.

First, little to no bleaching was observed at sites prior to the Hurricane in June and July 2019. While it is recognized that these surveys were conducted early in the summer and water temperatures may not have reached bleaching levels at that time, there were reports of bleaching in July 2019 from other parts of The Bahamas. Moreover, several reefs surveyed after Hurricane Dorian were visited the week immediately prior to Hurricane Dorian as part of coral spawning assessments conducted in the area by PIMS, including Sandy Cay Reef (Sites 13 & 14), Mermaid Reef (Site 16), Goole Reef (Site 12) and reefs in the Fowl Cays National Park (Sites 18 &21) with little bleaching observed.

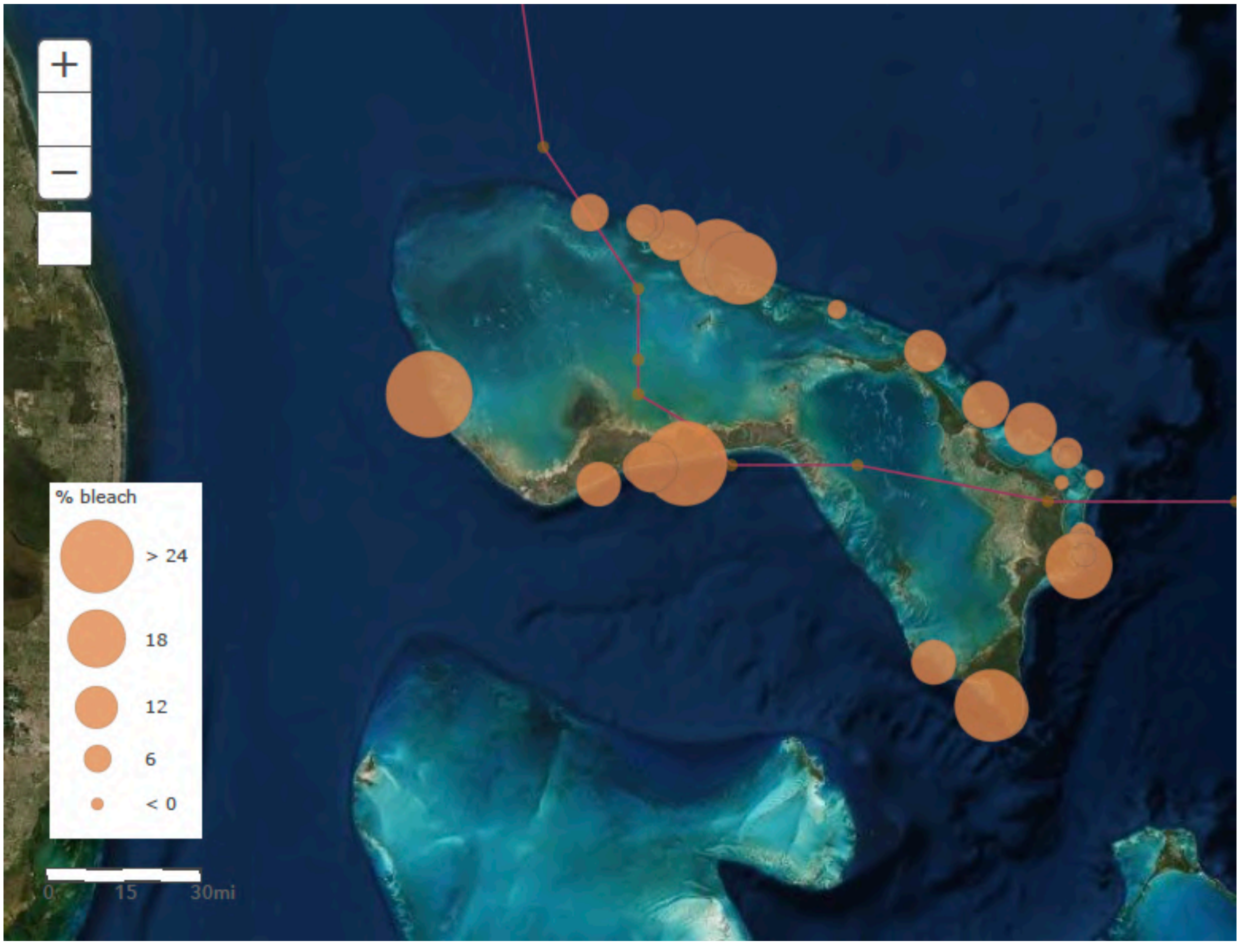


Figure 8. Percentage of corals surveyed that were bleached across all sites surveyed in October 2019.

At several sites, temperature loggers were in place through the storm period, showing a sharp decrease in water temperature with the passage of Hurricane Dorian, followed by a rise to normal seasonal temperatures within 7-10 days after the storm. Sudden temperature shock may have played a role in coral bleaching at some sites. In addition to temperature, siltation after the storm, including increased water turbidity and settlement of silt onto reefs may have also played a significant role in bleaching. Three of the sites with the highest amounts of coral bleaching (Sites 1, 6 and 24) all had significant amounts of silt at the time of surveys and evidence of mass sediment transport from inshore areas to the reef.

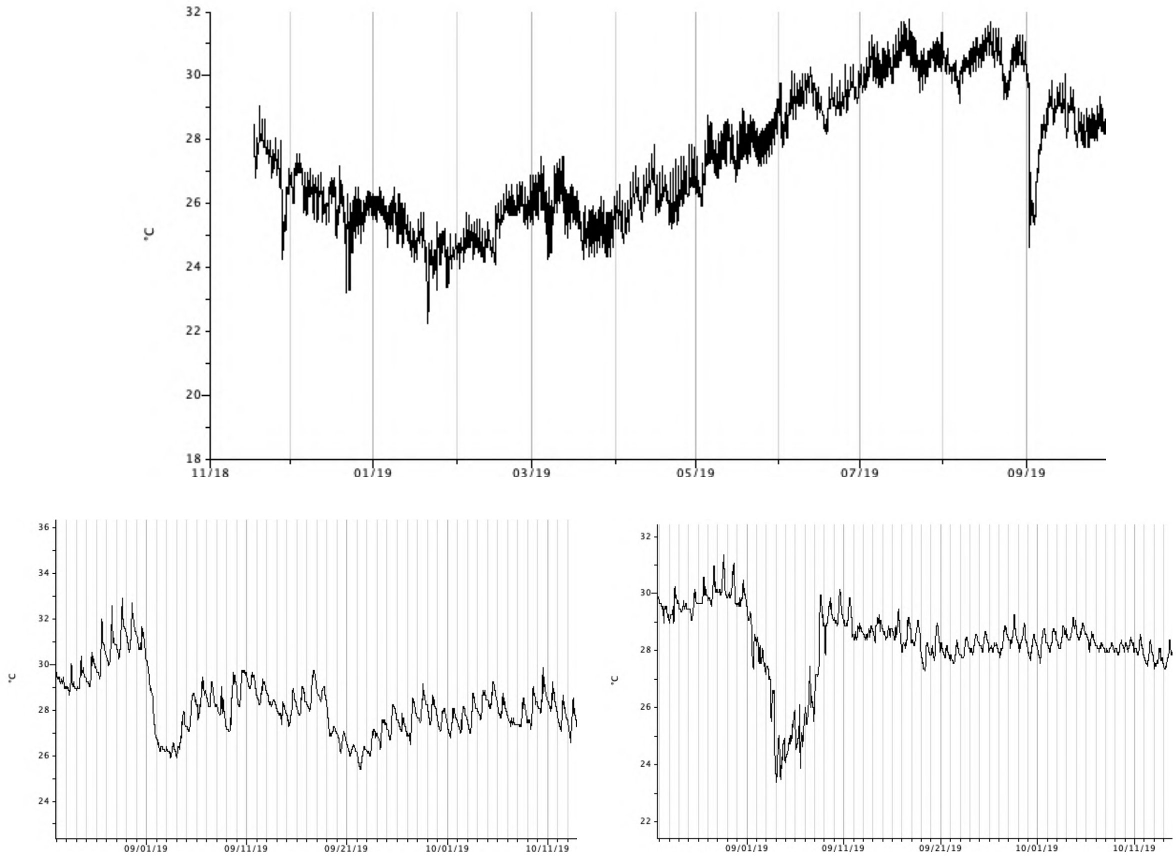


Figure 9. Temperature logs for Site 2 in the Peterson Cay National Park (Top), Site 16 at Mermaid Reef (bottom left), and Site 13 at Sandy Cay Reef in the Pelican Cays Land and Sea Park (bottom right). A full time series for each site from the time of deployment of the temperature logger is presented. Note the temperature scale differs on each site. All sites show a decrease in temperature of approximately 6° C on August 30-September 1, 2019 when Hurricane Dorian began to affect each site.

Other factors like changes in salinity due to large inputs of rainwater as the storm stalled over the Little Bahama Bank may have also contributed to bleaching. Reports from blue holes on Abaco indicate that the freshwater lens expanded due to heavy rains during the storm (B. Kakuk personal communication). This may have contributed to local bleaching events in shallow areas, but at several sites surveyed, bleaching increased at depth or was very species specific (*Orbicella faveolata*, *Pseudodiploria strigosa* and *Millipora* spp. being most affected), so changes in salinity are not as likely as other causes of bleaching. We are currently in discussions with physical oceanographers to determine what conditions were like at reefs during the storm and modeling environmental parameters to better determine sources of stress to corals that may have resulted in bleaching.

Other Changes to Benthic Communities

In addition to coral cover, AGRRA benthic point intercept surveys provide information on the percent cover of other key components of benthic communities including organisms that compete for space on reefs with coral, such as:

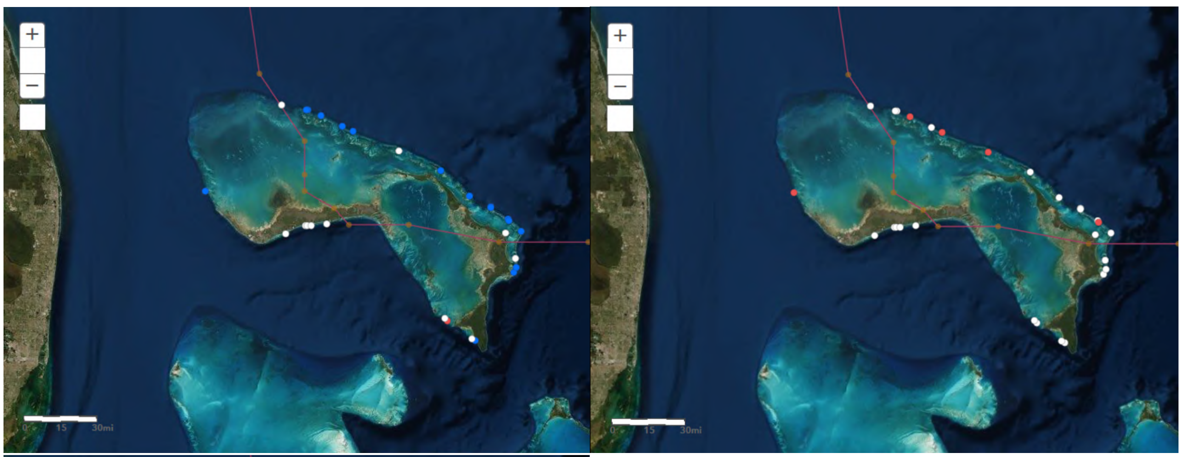
- Fleshy macroalgae (FMA) - seaweeds that can overgrow corals preventing recruitment of juveniles and even smothering smaller colonies
- Turf algae (TA) - short patches of unidentified algae that rapidly colonize reefs when other organisms like corals die
- Turf algae and sediment mats (TAS) – dense patches of turf algae that trap sediment which can prevent coral larvae from settling to the reef, smother small corals, and may harbour pathogens that can kill corals.

As stated earlier, hurricanes may affect all of these components of benthic communities, with positive and negative implications for reef health. As with changes to the percent cover of live coral on reefs, we examined the change in the percent cover of these reef components separately on a site by site basis by comparing the percent of space occupied by each of these components in multiple replicate transects before and after Hurricane Dorian using a non-parametric Mann-Whitney U test.

Fleshy macroalgae (FMA) is one of the biggest competitors or corals and can essentially overgrow them or prevent larval recruitment to the reef when FMA is left unchecked. FMA can rapidly overtake a reef under conditions where nutrient inputs are high or where there have been declines in grazing species on reefs, primarily the long-spined sea urchin (*Diadema antillarum*) and to a lesser extent parrotfishes (Scaridae) and surgeonfishes (Acanthuridae). Prior to Hurricane Dorian, most reefs surveyed along the Little Bahama Bank were dominated by FMA. The force of waves associated with hurricanes, however, can detach FMA from reefs, removing much of its biomass and reducing the amount of coverage on reefs. Because hurricanes typically occur during peak spawning and recruitment times for corals, it is hypothesized that hurricanes may have a positive effect on coral reefs by removing FMA and allowing corals to recruit to reefs. We found a significant reduction in the amount of FMA on 16 of the reefs surveyed before and after the storm and a significant increase in macroalgae on only one reef ($p < 0.05$; Fig. 10). In an extreme case, site WGB007 went from having 64.2% cover by FMA in July 2019 to only 1.2% cover in October 2019 after the storm.

For the reduction on FMA to have a positive impact on coral reefs, however, the reduction in FMA must (1) persist for an extended period of time, and (2) not be replaced by an increase in other harmful organisms such as turf algae that traps sediment (TAS). The former condition can only be determined by monitoring benthic communities over an extended period of time. Our surveys did, however shed light on the latter condition.

Turf algae and sediment increased at four sites surveyed ($p < 0.05$; Fig. 10). Most of these sites were close to large areas of exposed banks where sediments were resuspended during the storm and reefs were covered with a fine layer of silt and organic muds that became trapped in turf algae. At some sites like Site 1 and Site 24, the base of reefs were buried in a mix of carbonate silt, and seagrass detritus up to 1 m in depth, and much of the reef was covered in silt. At Site 1 where we saw a dramatic decrease in FMA, TAS had a concurrent increase from 0.2% of the seafloor in July 2019 to 86% of the reef in October 2019. A major concern at these sites where FMA increased significantly is that the TAS will harbour pathogens that lead to increased incidence of coral disease in the future. Turf algae also increased in abundance at four reef sites ($p < 0.05$; Fig. 10), which may result in increases to TAS over time or may be a precursor to growth of FMA. Sites where TA decreased significantly were Site 1 off West End Grand Bahama, where TA was converted to TAS due to high levels of sedimentation, and site 15 off Elbow Cay which had a decrease in both FMA and TA, probably due to high wave energy as Hurricane Dorian made first landfall.



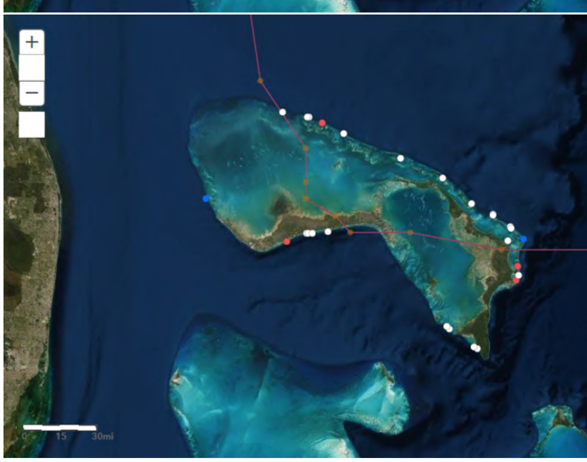


Fig 10. Changes to percent cover of FMA (top left), TAS (top right), and TA (bottom left). Sites with statistically significant ($p < 0.05$) reduction to FMA, TAS and TA are noted in blue, significant increases are noted in red, and sites with no significant changes in percent cover are indicated in white.

All three of these benthic components had the greatest short-term changes from Hurricane Dorian along the northern sections of the Abaco Barrier reef and one site surveyed off the northwest of West End, Grand Bahama. This is likely due to exposure to high wave energy from Dorian without the shelter of a large land mass to dissipate wave energy and proximity to expanses of soft sediment on the Great Bahama Bank which was stirred up during the storm. Monitoring recovery of these reefs for the next 1-3 years will be necessary to determine if the loss in FMA leads to any increases in coral recruitment or if they return to FMA-dominated communities with low coral cover.

Fish Biomass

Most studies of hurricanes have focused on changes to benthic communities and damage to reef structure, but we also noted changes to fish populations. While a more thorough analysis of reef fish community structure using data collected before and after the hurricane is in progress, a preliminary analysis of changes in total fish biomass was conducted for this report. For all fish taxa included in AGRRA surveys, species-specific biomass was calculated based on the number of fish observed for each species in 5-10 cm size classes using length-weight equations available for each species (see www.fishbase.org for parameters to convert length to biomass for each species). Total biomass for each transect was calculated as the sum of species-specific biomass for all fish observed.

A comparison of biomass at each site before and after Hurricane Dorian was conducted using an ANOVA . This analysis revealed that there were significant decreases in fish populations at three sites and a slight but significant increase in total fish biomass at one site (Fig. 11). At two sites, Mermaid Reef (Site 16; $p < 0.01$) and Site 24 ($p < 0.01$) fish biomass decreased by an order of magnitude. Most noticeable was the decrease in large parrotfish at these sites, which may have implications for grazing rates and FMA growth at these sites over time. The increase in fish biomass at Morraine Cay Reef (Site 23; $p = 0.032$) was likely due to the strong influence of one data point — the sighting of a large barracuda with high biomass in one transect after the storm. Smaller increases in parrotfish biomass after the storm may also have contributed, but are unlikely to have resulted in a significant change in biomass.

While it is unclear the exact cause for decreases in fish biomass, there may have been high mortality rates during or immediately after the storm due to injury, changes in reef structure and/or predation. Changes in primary producers (e.g., FMA and TA) may have also contributed to shifts in fish biomass. Long-term impacts associated with changes to reef structure and primary production s may continue to shape fish communities over time. A more detailed assessment of how fish community structure and size distribution was altered by the storm may reveal further insights into how Hurricane Dorian affected fish populations (e.g., Kaufman 1983).

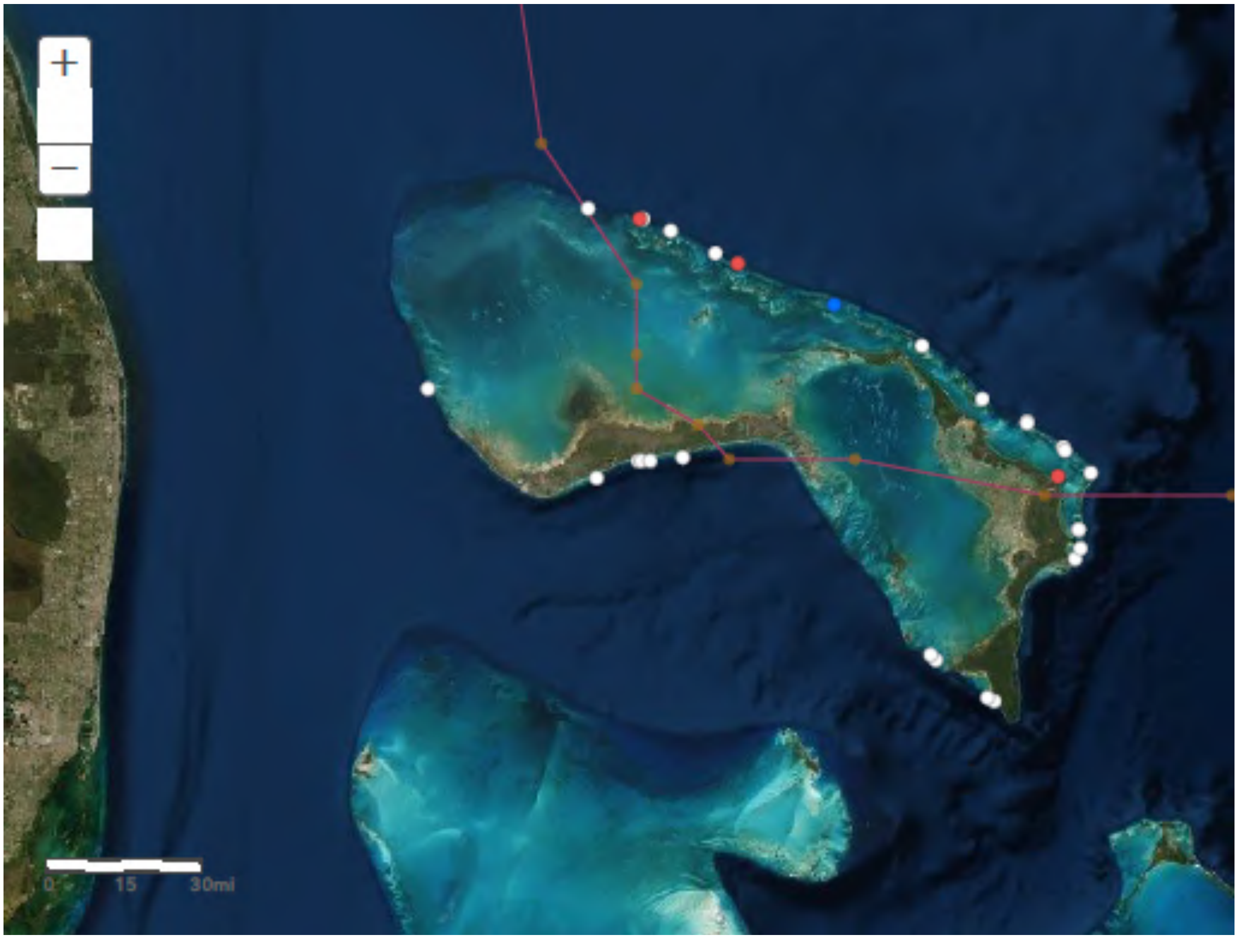


Fig 11. Changes to fish biomass from before and after Hurricane Dorian. Sites with statistically significant ($p < 0.05$) reduction in total fish biomass are noted in red, significant increases are noted in blue, and sites with no significant changes in fish biomass are indicated in white.

Additional Observations

While AGRRA surveys quantify anthropogenic "trash" observed in transects, these data are limited due to sampling constraints, but our Hurricane Damage Index (HDI) provides a relative scaling of debris on reefs. Thus, additional observations are required to shed more light on the amount and type of debris on reefs, and the impact of that debris. Sites that had the most debris were ones in close proximity to shore, either due to debris from homes that was washed out to reefs as in the case of Mermaid reef, where there were observations of household appliances and other contents of nearby homes, e.g. car parts, roofing and other construction materials. The greatest damage from debris however, both at Mermaid Reef and Site 6 off High Rock, Grand Bahama near the Equinor oil facility was not from anthropogenic debris, but from natural terrestrial debris, particularly invasive Casuarina trees. Because Casuarinas dominate sandy shorelines in many areas and have shallow root systems that do not stabilize sediment, they often fall over during storm events and increase beach erosion. This not only presents a problem of increased sedimentation during storms, but during high storm surges, entire trees may be moved by water. In the case of dense wood like that of Casuarina, it does not float, and the sunken tree trunk rolls across the sea floor destroying reef structure in its path. At Mermaid Reef, the damage from Casuarina is visible in the photomosaic images showing tree trunks on the seafloor that have toppled large coral heads. This was also the case at Site 6, where trees detached coral heads and killed soft corals and other organisms their path to nearly a kilometer (0.6 miles) offshore in depths of over 15 m (Photo 1). This presents yet another reason to remove Casuarinas from shorelines to protect coral reefs in storm events.

Photo 1. Damage to reefs from Casuarina trees at Site 6 (both top and bottom left), and Mermaid Reef (Site 16, bottom right).

Another observation not captured during AGRRA surveys was the fact that coral nurseries that were established by the Perry Institute for Marine Science and local partners as part of the Reef Rescue Network all survived Hurricane Dorian with minimal losses of corals and damage to nurseries. This includes PVC tree nurseries established in the Fowl Cays National Park of Abaco and in Lucayan National Park and Petersen Cay National Park off Grand Bahama, as well as line nurseries off Castaway Cay in southern Abaco. The resilience of these nurseries and the health of corals on the nurseries will play an important role in recovery of reefs where fragile branching *Acropora* spp. corals (elkhorn and staghorn corals) were damaged by Dorian or had died prior to that due to temperature stress, disease and other impacts.

Finally, observations of large-scale reef features using a drone (Mavic Pro2 with a Hasselblad camera and a polarizing filter) revealed severe structural changes to reef crest areas in the northern Abaco Barrier Reef between sites 24 and 26. Images form this area show large fractures in the reef structure that are believed to have been created by wave action during Hurricane Dorian and the "calving" of large pieces of reef (up to 30 m in diameter) which split from the rest of the reef structure and collapsed to the sea floor (Photo 2). In some cases where the width of the reef structure that detached and collapsed to the sea floor was greater than the depth of water at the site, emergent rock structure was visible where none had existed previously. Unfortunately, in-water assessments of these areas were not possible in October 2019 due to the difficulty with bringing a large research vessel to these sites. Further assessment of these areas is needed to determine the extent of these changes and assess impacts to reef organisms.

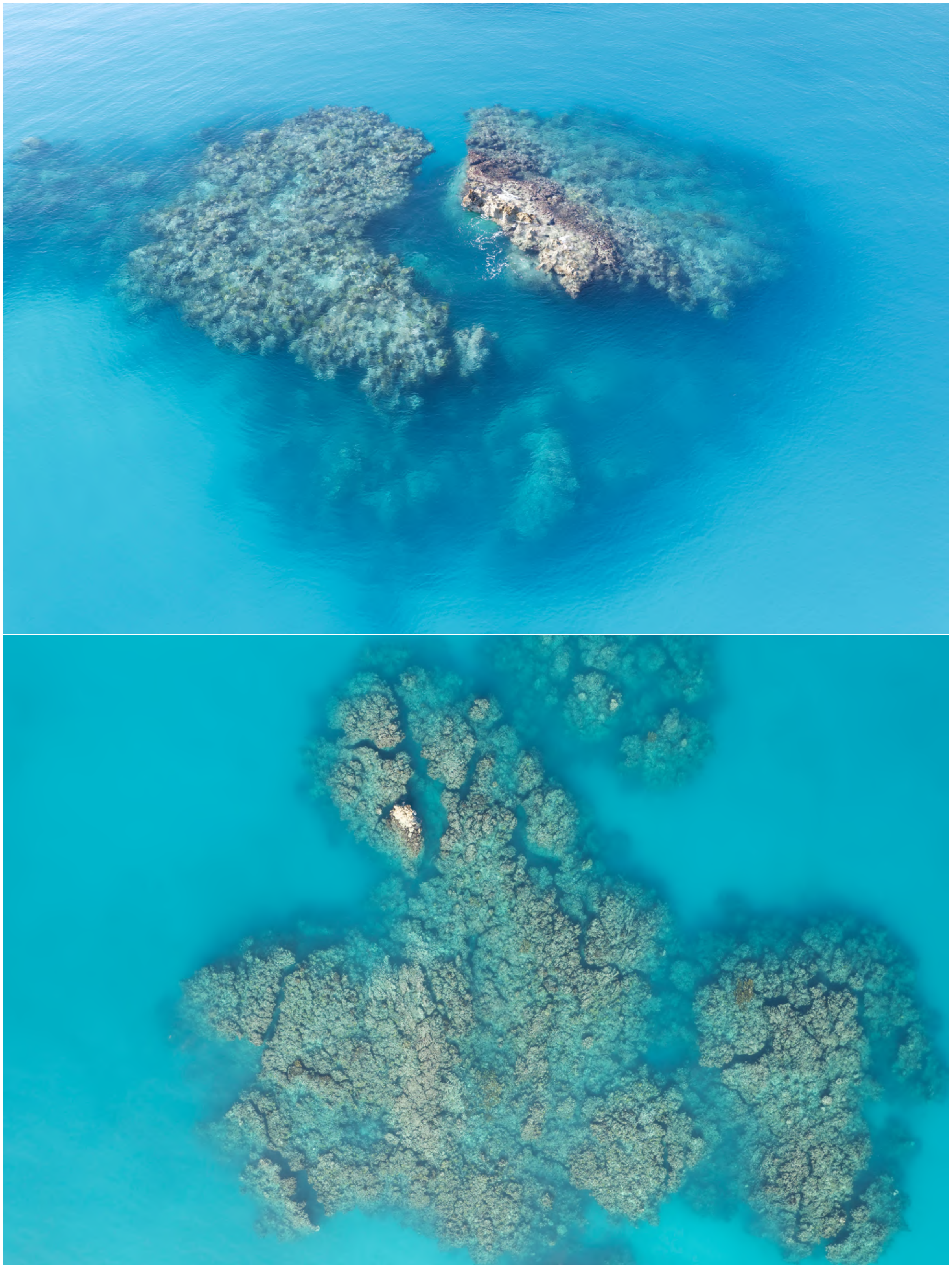


Photo 2. Two areas along the northern Abaco Barrier Reef where Hurricane Dorian fractured and collapsed reef structure resulting in emergent rocks where none had been observed or charted before the storm.

Conclusions and Recommendations

Hurricane Dorian caused significant damage to many reefs around Abaco and Grand Bahama, however the type and severity of that damage varied greatly among sites and in ways that were not clearly correlated with characteristics of the reef (e.g., depth or type of corals present) or the storm (e.g., distance from eye of the storm, or intensity of the storm). For example, elkhorn coral reefs of Sandy Cay Reef in the Pelican Cays Land and Sea Park (Site 13) showed little to no damage to coral colonies despite being at the southern eyewall of the storm as it made its initial landfall as a maximum strength hurricane, but Goole Reef (Site 12), just 5 km away saw much greater fragmentation of elkhorn coral, and Morraine Cay Reef (Site 23) which was over 50 km from the center of circulation of the storm received severe damage to elkhorn coral (Photo 3). Further analyses combining environmental conditions during the storm and observed patterns of damage may provide greater insights into why some sites were devastated but many others were spared. The fact that so many reefs throughout the area did not suffer severe damage to reef structure, loss of coral, fragmentation, or siltation is encouraging and provides some hope that there will be significant natural recovery that can support local communities and replenish reefs where significant damage occurred. Because hurricane impacts may continue to result in coral loss for a year or more after the storm (e.g., Gardner et al. 2005)



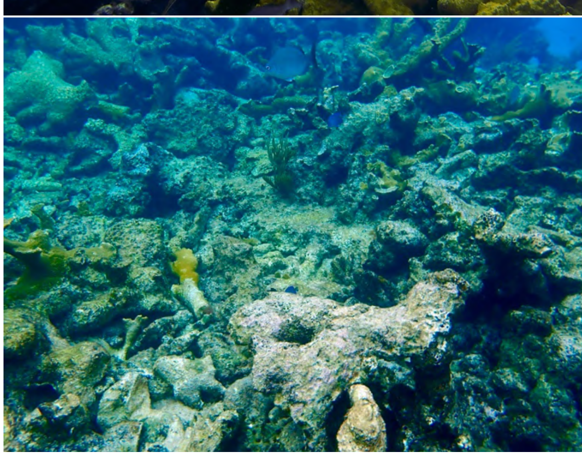


Photo 3. Elkhorn coral (*Acropora palmata*) stands from Sandy Cay Reef (Site 13), Goole Reef (Site 12) and Moraine Cay Reef (Site 23) which saw variable damage from Hurricane Dorian.

While the data presented in this report represents one of the better datasets on hurricane damage in The Bahamas and throughout the Caribbean region, this study was designed to be a preliminary examination of the impacts of Hurricane Dorian across a large area. Based on these results, we can make specific recommendations for further data collection and analysis that may inform management and contribute to developing strategies to help areas affected by Dorian to recover and/or strategies to deal with future storm events throughout The Bahamas. These additional studies include:

1. Addressing gaps of this reef assessment by assessing the condition of reefs in areas where we were not able to conduct many assessments, including more reefs along the western margin of the Little Bahama Bank, East Grand Bahama, SE Abaco, and even sections of the northern Abaco Barrier Reef between sites 21 and 24 in this study.

2. Further assessments of reefs in some of the hardest hit areas, including West End , East Grand Bahama , Shallow reefs near Marsh Harbour and reefs in the northern Abaco Barrier Reef between site 24 off Stranger Cay and Grand Cay.

3. Assessments of non-reef habitats including mangroves and seagrass beds. the Perry Institute for Marine Science and partners (e.g., Bahamas National Trust), have data from conch populations, seagrass beds, mangrove habitats and juvenile reef fish living in mangroves from various locations around the Little Bahama Bank. Coupled with published reports from other researchers, this baseline data can be used to assess damage to these habitats and populations relying on them.

4. Continued monitoring of sites assessed in this study and others to evaluate recovery rates for reefs and key species, and to determine how interventions such as restoration or protective management affects recovery of populations and ecosystems.

5. Additional assays should be conducted, including chemical analysis of water and sediments, eDNA analysis and sampling of tissues of various species to determine how Dorian may have changed water quality (e.g. anthropogenic nutrients and chemicals like petroleum that may have been released into the water and other environmental parameters (e.g. sediment erosion from land) and its impact on key species and ecosystems.

6. Once we have more data from Abaco and Grand Bahama, these data can be combined with data from other storm events to conduct a more thorough risk analysis for hurricane damage to Bahamian coral reefs (and other marine habitats), similar to analyses performed for terrestrial areas of The Bahamas (e.g., Sealy and Strobl 2017, Silver et al. 2019)

There is also a need for interventions to help with the recovery of coral reefs and key species. Similarly, we can use lessons learned from Dorian to improve our response to disasters in the future. These actions include:

1. Creation of additional marine protected areas in the region to build resilience in marine ecosystems. This will promote natural recovery following storms and other threats that case marine systems to decline and result in the loss of valuable ecosystem services. A network of these areas can also replenish surrounding unprotected systems promoting recovery of ecosystems throughout the region.

2. Removal of debris from reefs and other areas throughout Abaco and Grand Bahama. Debris continues to pose a threat to marine ecosystems and may have long-term impacts on them, as well as potentially presenting navigation or health hazards to people.

3. Removal of invasive Casuarina trees from coastal areas. While this is a large task, these trees exacerbated hurricane impacts more than any other factor and led to significant coastal erosion and damage to land.

4. Restoration of corals to key reef areas to help "jump-start" the recovery process. This can be done by scaling up existing *in situ* nurseries as well as other coral restoration techniques that we have been testing in The Bahamas for the past 2-3 years including microfragmentation and larval propagation.

5. Develop a rapid response protocol for responding to disasters in The Bahamas to conduct assessments of damage to marine systems and rapidly implement strategies to improve ecosystem recovery (e.g., debris removal, repositioning and stabilizing corals, etc.).

These measures and others should be part of a strategic conversation involving government policy makers, marine resource managers, conservation practitioners and scientists. These conversations should lead to strategies that can be implemented with sufficient funding, local capacity, and in a timely manner.

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