Perry Institute for Marine Science/Bahamas Undersea Research Foundation Post-Dorian Mangrove Restoration Plan

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Overview

At the interface between land and sea, mangroves are among the most productive and valuable ecosystems in The Bahamas. Mangroves serve critical ecological functions and provide invaluable ecosystem services including serving as nursery habitat for reef fish and key fishery species, protecting coasts from erosion, and serving as a carbon sink to reduce the impact of CO_2 emissions on climate change. Their position between the ocean and land, however, makes them particularly vulnerable to damage from hurricanes. Although uniquely adapted to live in areas where they are exposed to salt water tidally and serve a critical function of protecting shorelines the waves and inundation with seawater during storms, severe hurricanes can cause significant damage to mangrove systems as inundation by pooling salt water for extensive periods can kill mangrove plants (e.g., Lagomassino et al. 2021).

Hurricane Dorian struck mangrove systems in central Abaco as the most powerful storm ever recorded in the Atlantic, battering the island with winds of over 180 mph (290 km/h) and a storm surge of over 7 meters, before hitting East Grand Bahama and lingering between the two islands as a major hurricane for over a day before moving northward and exiting The Bahamas, leaving behind a wake of destruction on land and in the sea. Subject to both the extreme winds, inundation my storm surge and powerful waves, mangroves did not escape this devastation. Initial reports from Sentinel-2 satellite images with 10m resolution before and after the storm indicates that 91.17 km^2 of mangroves on Grand Bahama or 73.77% of the island's mangrove area damaged or destroyed and 87.73 km^2 or 40.12% of mangroves were damaged or destroyed for Abaco (Steinberg et al. 2020). But these numbers were derived from low resolution imagery, somewhat limiting its utility for accurately determining the extent of mangrove areas for both islands, let alone determine impact to those areas in a meaningful way. Furthermore, the binary classification scheme used lumped all mangroves into either the category of healthy mangroves or “damaged or destroyed” mangroves. The very broad category of “damaged or destroyed” does little to inform natural resource managers and others about whether a site will make a natural recovery, requires intervention to assist with recovery, or what that intervention should be. Finally, assessments based on satellite imagery alone cannot provide information on whether Dorian changed of the function or value of mangrove ecosystems, such as their role as fish habitat.

In July and August 2021, The Perry Institute for Marine Science, with assistance from the Bahamas National Trust, and funding from BPAF, conducted assessments of mangroves at 19 sites on Grand Bahama and 15 sites on Abaco.

During these assessments, PIMS staff assessed:

1. Current living and dead mangrove cover
2. Water quality parameters
3. Benthic communities and sediment depth
4. Mangrove fish communities

Many of the sites sampled were ones for which prior *in situ* data from before Dorian (2013-2019) had been collected for comparison of conditions before and after the storm. Several sites sampled (n=4) were ones where Bonefish and Tarpon Trust had already begun restoration efforts, so that these sites may be quantitative monitoring and evaluation can begin.

During aerial surveys, Living and dead mangrove cover was determined using data collected from a drone flown at 400’ (122m) elevation equipped with a 45 MP camera and sensors detecting 10 bands of multispectral light, with data collected from light bands with wavelengths above and below the visible light spectrum as well as within the visible light spectrum. Resolution of visual images was ~1 cm per pixel with the camera and 8 cm per pixel with the multispectral sensor. For each location, mangroves and some surrounding area were mapped covering 27 to 506 acres per site for a total of nearly 6,700 acres mapped across all sites (Figure 1). Data was processed to compile photomosaics of each mapped area which were then assessed using different products from the visual and multispectral data, including a Normalized Difference Vegetative Index (NDVI), a metric used to indicate amount of photosynthetic activity in an area. The NDVI values and GIS maps of mangrove habitat (S. Schill, TNC unpublished data) were used in analyses to compare total area at each site that was living versus dead mangroves and evaluate small scale recovery including regrowth of mangroves damaged during Dorian or new recruits to the system.

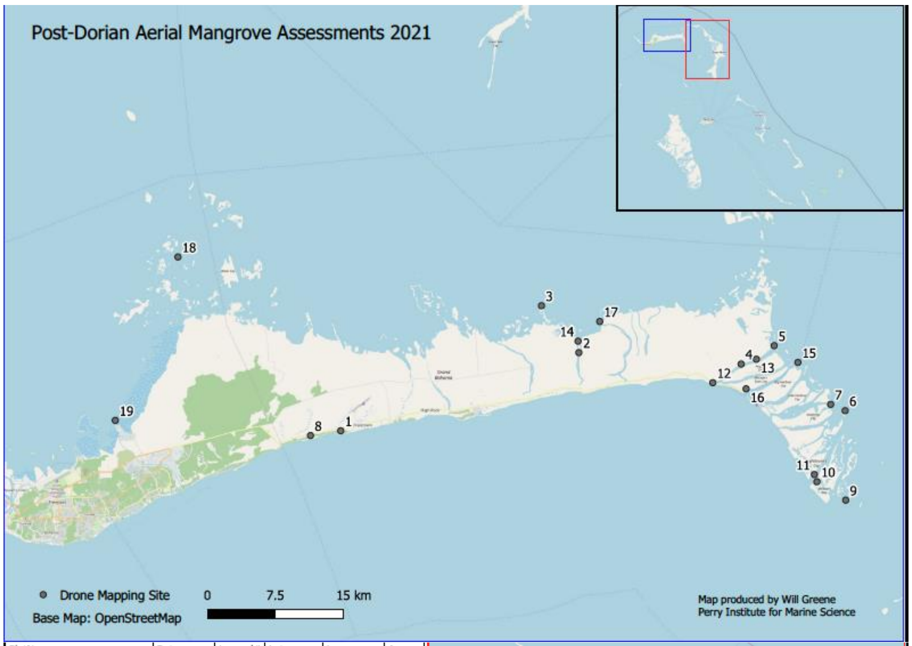
In addition, to drone imagery, Planet Dove Satellite data (4m resolution) was used to provide maps of mangrove living cover before and after Dorian across all of Grand Bahama and Abaco. Additional analyses using WorldView Satellite data (50cm) resolution is underway to further refine damage estimates across broad spatial scales.

Where possible *in situ* assessments included water quality parameters sampled through the water column at each study site using a YSI ProDSS meter equipped with sensors measuring:

1. Position of the sample
2. Depth
3. Temperature
4. Salinity
5. Turbidity
6. Chlorophyl A

In addition to environmental parameters, point intercept transects (10m long with points at 10cm intervals) were used to measure benthic cover perpendicular to the mangrove shoreline into the creek or surrounding marine environment, with 1-2 transects surveyed per site.

Along one transect per site sediment depth was also measured with a scaled probe pushed into the sediment until it hit bedrock. Finally, a minimum of three belt transects measuring 30m by 2 m were conducted per site where all fish were identified to the species (or family for some of the smaller “baitfish”) and size estimated to the nearest cm. Transects followed the contours of the mangrove shoreline and all fish from the outer edge of the mangroves to 2 m into the mangrove roots were recorded. For at least 2 transects per site, depth was also recorded at 5 m intervals.



PlotName	Date	Legend#	Lat	Lon	Area
Gold Rock Creek	2021-07-24	1	26.604765	-78.381782	506.57
Gap Creek	2021-07-25	2	26.681892	-78.118127	225.61
North Riding Point	2021-07-25	3	26.728157	-78.159522	199.17
August Creek 1	2021-07-26	4	26.670629	-77.93839	177.17
August Creek 2	2021-07-26	5	26.688766	-77.901858	90.19
EGBM8	2021-07-26	6	26.624584	-77.823253	98.1
EGBM11	2021-07-26	7	26.630843	-77.839295	20.68
Gold Rock Creek West	2021-07-26	8	26.60008	-78.415286	467.03
EGBM1	2021-07-27	9	26.536273	-77.822705	216.96
EGBM6	2021-07-27	10	26.554475	-77.854495	205.84
EGBM5	2021-07-27	11	26.561554	-77.857293	90.44
MacleansTownCreek	2021-07-27	12	26.652235	-77.969808	213.25
August Creek Cut	2021-07-28	13	26.675392	-77.921552	269.34
Gap Creek 2	2021-07-28	14	26.693193	-78.118982	193.73
MacleansTownCreekMouth	2021-07-28	15	26.672242	-77.875553	199.91
MacleansTownDockMangrove	2021-07-29	16	26.646205	-77.932931	190.02
Ridge Creek Mouth	2021-07-29	17	26.712591	-78.095002	215.23
Water Cay 1	2021-07-29	18	26.776212	-78.562035	243.65
Dover Sound	2021-07-29	19	26.615041	-78.63142	203.12
ABM1	2021-07-31	20	26.682798	-77.306989	190.27
ABM2	2021-07-31	21	26.667725	-77.29591	192.74
Treasure Cay SW	2021-07-31	22	26.632513	-77.29269	220.17
ABM3	2021-08-01	23	26.917451	-77.804447	142.58
ABM4	2021-08-01	24	26.908854	-77.72685	209.05
ABM5	2021-08-01	25	26.901622	-77.580231	178.41
Treasure Cay West	2021-08-01	26	26.714264	-77.34505	229.07
Crossing Rocks	2021-08-02	27	26.146912	-77.19448	225.11
Sandy Point Mangroves	2021-08-02	28	26.018003	-77.395385	204.11
SnakeCreek	2021-08-03	29	26.45038	-77.056419	291.58
North Marls	2021-08-03	30	26.569828	-77.146371	94.89
Black Sound Cay NP	2021-08-04	31	26.759621	-77.321195	27.18
Cherokee	2021-08-05	32	26.284859	-77.057905	92.17
ABM9	2021-08-05	33	26.29555	-77.087531	170.75

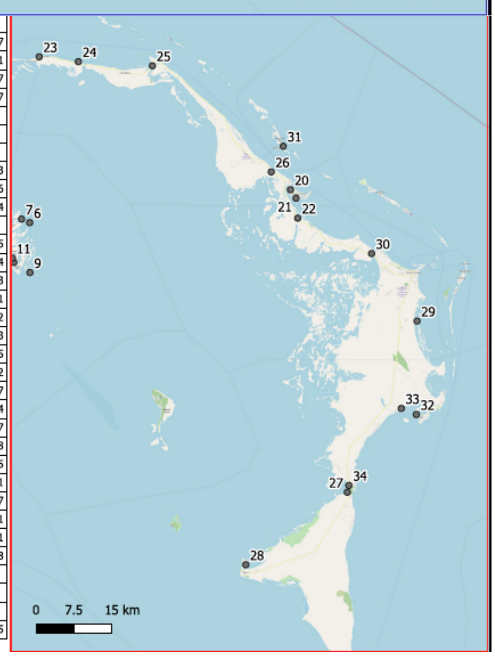


Figure 1. Map of study sites showing location of mangroves mapped for Grand Bahama (Top) and Abaco (Bottom) along with a table showing the coordinates and number of acres mapped at each site.

Assessments were conducted across a range of sites on both islands with a focus on:

1. Sites indicated by stakeholders as having suffered high impacts by hurricane Dorian
2. Within areas identified as a priority, sites for which before storm data existed
3. Sites where some restoration had already occurred
4. A few sites that may serve as controls that saw minimal impact from Dorian were also surveyed for comparison

A summary of the results from these surveys includes:

1. Red mangroves (*Rhizophora mangle*) which dominated the mangrove shoreline of both islands saw the greatest impact.
2. Previous satellite-based assessments of mangroves both (1) underestimated the total mangrove area of the islands, since mangrove fringes to creeks were not identified in these analyses; and (2) overestimated damage in many locations, where mangroves had either recovered from Dorian or saw minimal effects but were lumped into the "Damaged or destroyed" category.
3. Fish and benthic communities saw minimal impact from Dorian to date, as much of the mangroves that were killed by the storm remained "standing dead", still providing habitat for fish. However, dead mangroves were already showing signs of decay, which could reduce habitat quality dramatically within 3-5 years unless mangroves start to recover
4. In most locations the substrate and benthic communities did not vary between affected and unaffected mangroves, but there were a number of locations where the peat substrate formed by mangrove roots was exposed and eroded, which may have significant impacts on the ability of mangroves to recover on those areas. In one site off Abaco, large chunks of peat substrate were transported from where they naturally occurred and deposited throughout a creek and mangrove system.
5. In many locations there was a significant area of dead mangroves with some areas even having the mangrove trees removed by Dorian entirely, but in other areas there were significant signs of natural recruitment and recovery within 2 years of Dorian's impact (Figure 2).

Prioritizing sites

Clearly the damage caused by Hurricane Dorian is significant with thousands of acres of mangroves impacted, but evidence of natural recovery in some places suggests that all areas may not require intervention. Resources for restoring these mangrove areas are limited, so we must prioritize restoration efforts to ensure that we are restoring the areas that require intervention and will provide the greatest impact. Using available data from our in-water surveys, aerial surveys, and access to improved satellite data, we have developed a site prioritization or ranking system to prioritize restoration efforts in the locations that received the highest levels of mangrove loss and show low levels of natural resilience, as well as those of other intrinsic value. Prioritization is based on quantitative data collected during the assessments and satellite imagery and applies a ranking system for specific indices to select sites where the greatest restoration impact may be made. We are applying the ranking system using multiple metrics in a stepwise manner to filter sites for consideration for restoration.

Damage Index - The first ranking index is based on the extent to which mangroves were lost in an area. Using multispectral remote sensing data from high-resolution satellite imagery (50cm – 4 m resolution) Normalized Difference Vegetation Index (NDVI) values were calculated for mangrove areas (using The Nature Conservancy's base maps of mangrove areas) for the 6 months leading up to Hurricane Dorian as well as a year to two years after Dorian. Based on NDVI values the status and health of mangrove areas were determined before Dorian and compared with values of the same areas after Dorian. Priority areas for restoration will include those that had the greatest negative change in NDVI values, which tended to be mangrove areas with high canopy density before Dorian that show little to no living canopy after Dorian. A GIS map of the Damage Index can bee viewed using the link below: https://pims.maps.arcgis.com/apps/webappviewer/index.html?id=753cdacb9ea64d7e84ededbf99852e08

The user can zoom in on specific mangrove areas to view the damage index color coded ranking shown below where Mangroves colored dark red had the highest NDVI values (greatest canopy density) before Dorian in 2019 but were reduced to no detectable vegetation in 2021, almost 2 years after the storm). Lighter red and pink areas had less living vegetation in 2019 (e.g., sparse dwarf mangroves) but were also reduced to no detectable living vegetation in 2021. Cooler colors indicate sites where there was less mangrove loss.

2019-2021 Little Bahamas Bank Mangrove Change Analysis

NDVI Min	NDVI Max	Category	Explanation
-1	0.2	0	No vegetation detected
0.2	0.5	1	Sparse / low vegetation
0.5	0.6	2	Medium vegetation
0.6	1	3	Productive vegetation

2019 (Pre-storm)	2021 (Post-storm)				
		0	1	2	3
	0	00	01	02	03
	1	10	11	12	13
	2	20	21	22	23
	3	30	31	32	33

For our restoration efforts, only high to highest priority sites (red-orange) will be considered for mangrove replanting, but other restoration interventions may be considered if value ranking scores are high (see below).

Resilience Index - For sites where the Damage index is ranked as high or highest priority, a second index, the Resilience Index, will be calculated to prioritize restoration efforts. The resilience index examines the extent to which dead mangrove areas are recovering, primarily through the new mangrove recruits from propagules, but may also include new shoots from mangroves that were heavily damaged by Dorian but are starting to recover. Using aerial imagery collected from high resolution cameras and multispectral sensors on a drone, the number of recruits per acre/hectare will be determined (Figure 3). To estimate the recruitment index NDVI values from damaged areas will be calculated and within the damaged mangrove area. Five plots (3m radius circles) will then be selected at random within the area to count the number of discrete occurrences that are <30 cm in diameter where NDVI scores indicate live mangroves. The mean count for all plots will be used to determine the recruitment ranking for the site. Mean counts <5 recruit per plot will be ranked as highest priority, 5-10 high priority, 10-15 low priority, and >15 lowest priority. Note that replanting densities have been recommended to be as much as of 3,000 mangroves per hectare, which is equal to a mean density of 21 recruits per plot.

Value Index - Finally, we will apply an independent value ranking to all sites, regardless of whether the other two indices indicated a need for replanting. This index has two main purposes for prioritizing sites. For sites that are high or highest priority for replanting based on the two previous metrics, the value index will provide one more data point to rank the highest priority sites. For sites where replanting is not a high priority based on the two previous criteria, but other interventions may be recommended (e.g., hydrologic restoration, debris removal), this index will identify highest priority sites to dedicate resources to interventions.

The value index is a qualitative ranking based on the ecological function of mangroves, the ecosystem services they provide, and perceived value to local communities. Six metrics are included in this value index, with each metric producing a binary scoring of 1 or 0, which are added to provide the ranking on a scale of 1-6.:

- Social value – were the mangroves at the site identified as a priority area or high value area through community consultations (1= site was in the top 50% of priority sites identified in community consultations; 0 = site was not in top 50% of sites identified).
- Parks & protected areas – are the mangroves included in a national park or other designated protected area (1 = within protected area; 0 = not protected)
- Coastal protection – are the mangroves at the site serving as a buffer to protect infrastructure from wave and storm damage (1 = mangroves ≤1 km from infrastructure such as roads or settlements; 0 = mangroves >1km away from roads or settlements)
- Mangrove height – are the mangroves dwarf mangroves that produce relatively low numbers of propagules or tall (≥2m) which are far more productive. Taller mangroves

also provide greater value as bird habitat (1= mean height of mangroves ≥2m; 0= mean height <2 m).

- Fish diversity – Are mangroves at the site in the top 50% for supporting fish biodiversity around the island. (1 = fish biodiversity is in top 50%; 0 = fish biodiversity is in lower 50%).
- Fish biomass – Are mangroves at the site in the top 50% of sites for supporting fish biomass around the island (1 = fish biomass is in top 50%; 0 = fish biomass is in lower 50%).

In cases where replanting has been prioritized, the sum score of the value index (0-6) will be used as a final means of prioritizing sites that received equal rankings from the previous indices. In these cases, sites with the greater value ranking will have higher priority than those with lower rankings. In cases where replanting was not determined to be of value, but restoration may be needed the value ranking score will be used to prioritize sites to be considered for other restoration interventions. The benefit of the restoration and feasibility of the restoration will be considered on a case-by-case basis.

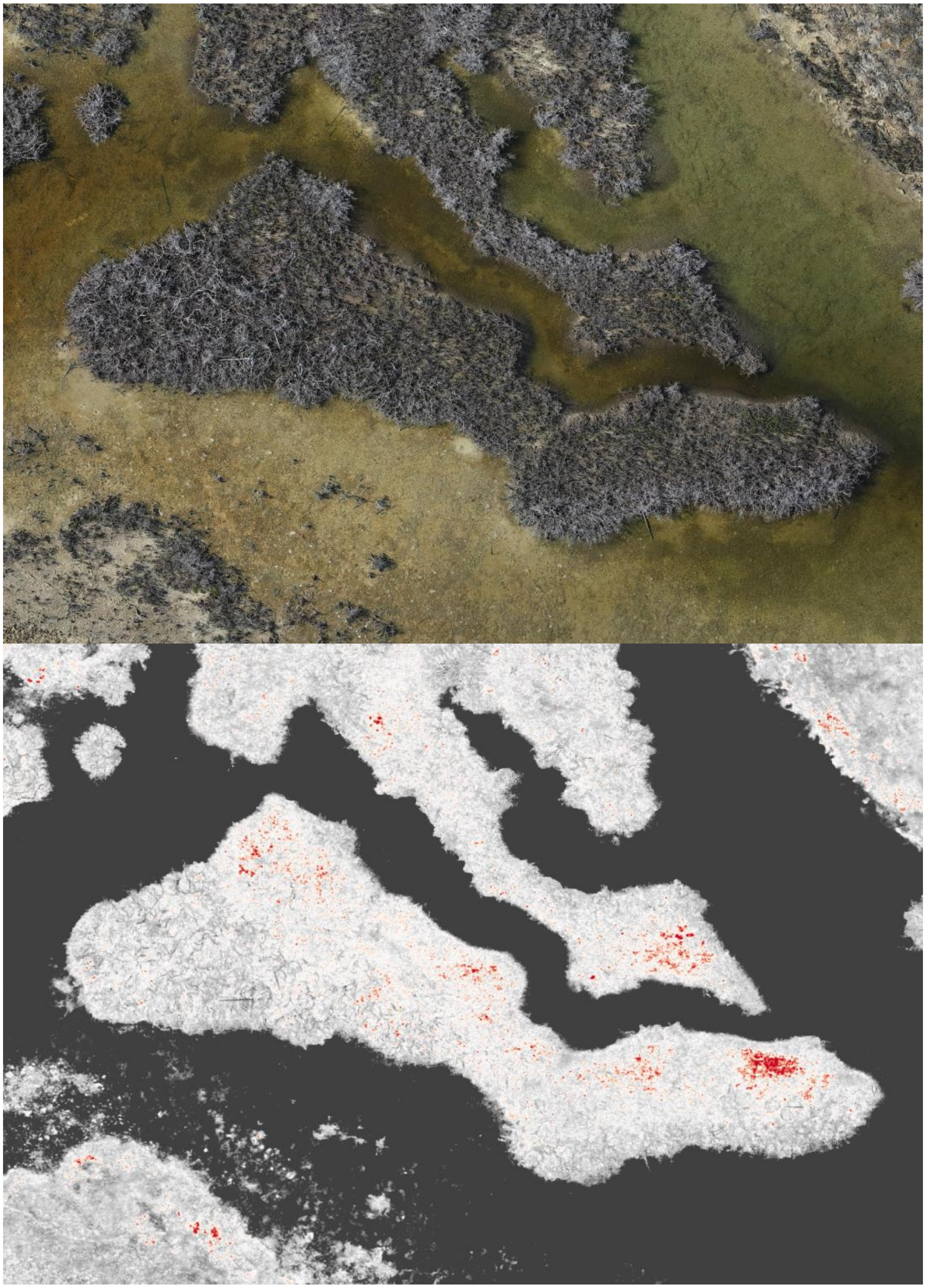


Figure 3. Drone imagery showing visual image of a section of damaged mangroves (Top) and NDVI data showing lining mangroves red and dead mangrove area in white/gray (bottom) to illustrate the extento to which mangrove damage occurred as well as levels of new recruitment in some areas. Despite high damage index scoring, this site may not require large-scale replanting due to relatively high recruitment or regrowth rates.

Applying ranking system
Using these criteria for assessing sites for Grand Bahama, most of the sites within the East Grand Bahama were determined to be highest priority based on the damage index. In the Northshore/Gap area, sites rankings varied more, with some sites being high or highest priority, but others rating as low priority. Sites along the south coast of Grand Bahama, such as Gold Rock Creek, ranked as low priority. The recruitment index, however, was quite variable across all high and highest priority sites around Grand Bahama, with many sites in the East Grand Bahama area ranking as having high to highest priority. The Value index indicated that although replanting may not be necessary, Gold Rock Creek was of high value and other restoration interventions should be considered there.

For Abaco, the damage index was high or highest, primarily on the west side of Abaco in the Marls between Treasure Cay and Marsh Harbour. Recruitment in most of the area, however, was higher than on Grand Bahama with fewer sites ranked as high or highest priority. It should be noted that inclement weather during the 2021 survey period prevented a comprehensive assessment of some of the smaller mangrove systems along the outer Cays of Abaco from Elbow Cay to the Northeast, and additional surveys of these areas may be needed based on relatively high value scores using available metrics. As such, these mangroves systems should be assessed further and prioritized as necessary.

Restoration solutions
There is no one size fits all approach to mangrove restoration and the intervention used to restore mangroves must be selected to address both the disturbance that has affected the mangrove system of interest and the scale at which that disturbance is affecting mangroves. For example, a mangrove creek system that has been altered by the building of a causeway that fragments the system requires a different solution than a mangrove shoreline that has been cleared to improve access to the water. In the case of the bisected creek system, hydrologic restoration that restores connectivity is required but the specific details of the intervention (installing a culvert, bridge or rerouting the road) may depend on the scale of the impact. IN the case of the mangrove clearing, replanting mangroves may address the issue or if the underlying soil has also been disturbed (regraded, covered with sand), additional interventions may be necessary.

In the case of hurricane Dorian's impacts to mangroves of Grand Bahama and Abaco, our assessments indicated that in most cases, the impact to mangroves was the death of mangroves, likely due to inundation by the storm surge for an extended period, leaving standing dead mangroves in most cases. In these cases, the primary restoration intervention should be replanting mangroves. As such, this will be the main strategy for restoration moving forward. At some locations, however, particularly in parts of Abaco like the outer cays from Elbow Cay to Green Turtle Cay, removal of debris from homes and sunken boats may also be necessary. Similarly, removal of destroyed docks and dislodged vegetation in Lucayan National Park and surrounding Gold Rock Creek system is needed. Hydrologic restoration, such as the removal of causeways or other blockages that fragment mangrove systems, and replacement of other coastal infrastructure that may have contributed to mangrove loss is beyond the scope of this project. However, other ongoing projects such as the IWECO and ICZM projects of the government of The Bahamas and Bahamas National Trust are likely to address these issues for mangroves on Grand Bahama.

As indicated earlier, the mass mortality of mangroves observed on Grand Bahama and Abaco suggests replanting as the most effective intervention to promote and accelerate recovery of mangrove systems. It is necessary to begin this recovery immediately where natural recovery is not occurring, or the ecosystem function may be compromised. For example, our assessments did not detect large scale differences in fish communities due to the death of mangroves, with fish using the structure provided by the roots of standing dead red mangroves, but nearly two years after Dorian, dead mangroves were observed to be deteriorating to the point where that structure is not likely to persist much longer. Therefore, promoting recovery before the standing dead mangroves deteriorate is needed to prevent changes in the value of mangroves for fish habitat. Furthermore, the root systems of standing dead mangroves act as a trap for new propagules to promote natural recruitment, even in areas where recruitment rates remain low. Loss of this structure will further slow the recovery process. Finally, the death of mangroves and deterioration of standing dead mangroves can result in a loss of mangrove peat which builds up the substrate and sequesters carbon. Compression or loss of this peat layer reduces the elevation of the substrate, changing its suitability of the area to support mangrove growth and the value of the area for coastal protection.

Mangrove replanting will follow best practices outlined in the Mangrove Action Project's *The Golden Rules for Mangrove Planting* (Enright and Wodehouse, 2019), including:

1. Make sure the site's land ownership issues are sorted out first and an agreement between all stakeholders is reached to ensure the mangroves are protected long-term
2. Understand why natural regeneration is not occurring or is not sufficient and then make adjustments to the site or find solutions to issues. If planting is required, plant the right species at the right time in the right place being aware of the local mangrove zonation of your restoration site. Remember mangroves occur naturally in the upper half of the intertidal zone.
3. Plant the same species close to where the species is naturally occurring as this follows nature. Try planting two or 2 propagules or seedlings close together in clumps or groups. Do not plant mangroves out in the open on mudflats or in seagrass beds
4. Do not plant mangroves in straight rows as mangroves do not naturally grow in straight lines and we don't want to create plantations. Straight rows ignore natural topography of the site and water channels. Straight row plantations are less effective as a buffer against waves
5. Do not plant mangroves too dense covering the entire area as this will restrict the opportunity for natural regeneration and higher biodiversity. Plant as many species as are naturally occurring at your site if possible.

6. Small-scale test planting is a wise way to assess your site, as mass planting could be setting you up for a big failure. Planting over time will allow you to observe results and make adjustments. This works better than one day mass planting events.
7. Do not plant in any water channels or tidal streams as this could restrict tidal flushing once trees grow.
8. Make sure the local community members are fully involved from the planting stage and its best if they take on stewardship or ownership of the project.
9. Make sure the site is protected from people, boats and livestock with fencing if needed. Signboard the site with a phone number so outsiders know that it's a restoration site
10. Plant seedlings, propagules or wildlings collected as close as possible to the restoration site. Do not move seeds from another country or region. If wildlings are used replant them immediately, preferably in the late afternoon
11. Monitor your site long-term (usually 5 years) and learn from both successes and failures and make necessary corrections and adjustments.

In addition to these guidelines, there are several additional considerations. There are different options for replanting mangroves, including directly replanting propagules or growing propagules in a nursery for a period before planting as saplings. Using either method, replanting may be accompanied by modification to the substrate to make it more suitable for growing mangroves, and for propagules planting may benefit from some form of encasement or protection. To date, mangrove restoration around Abaco and Grand Bahama has focused on growing propagules for several months to seedlings in off-site nurseries before planting them at restoration sites. In some circumstances, this method can improve survival of replanted mangroves, but a study conducted in The Bahamas in Bonefish Pond National Park compared the success of plots replanted with young red mangrove saplings, red mangrove propagules without encasements and mangrove propagules with encasements showed that planting propagules, regardless of the method, had greater survival and similar growth through at least three years of monitoring than mangroves grown in a nursery before planting (Knowles et al. 2013, Dahlgren unpublished data). Long-term monitoring is ongoing as part of this study, but other key findings were that saplings grown in different soil and/or salinity conditions from those of the study site had lowest survival rates, and that for any of the experimental mangrove planting methods, position of planting relative to tide height has a strong influence on survival, with mangroves in the upper 1/3 of the intertidal zone having lower survival than those planted in the upper 2/3 of the intertidal zone.

Because the success of planting propagules is similar to that of planting saplings, and in some cases more successful than planting saplings, and the fact that planting propagules is less resource intensive in terms of the time needed to grow plants, cost of maintaining nurseries, and number of mangroves that may be planted at a time (e.g., saplings grown in pots will take more space to transport to restoration sites and take more time to plant), we will focus our efforts on planting propagules.

Preliminary surveys of mangroves on both Grand Bahama and Abaco indicate that there are healthy mangrove populations on both islands which may serve as a source of propagules for restoration efforts. Obtaining mangroves locally also ensures the genetic integrity of local populations. Even though mangrove propagules are capable of long-distance dispersal, gaps in mangrove distribution can serve as barriers to gene flow (Binks et al.2018). In The Bahamas, this effect is evident in red mangroves, which show geographic population structure with limited gene flow between islands (A. Lundy MS Thesis, 2021). Furthermore, local genetics may be better adapted to local environmental conditions.

Propagules will be collected as soon as permits allow and will be conducted year-round. propagules will be planted within 40 days of collection, their typical dispersal period. Because peak propagule production is in the late summer and autumn, we will conduct a number of small-scale test plantings in winter and spring to assess feasibility and success rates before conducting larger scale restoration activities will take place from August through November annually for up to three years.

Post-Restoration Monitoring and Evaluation

All restoration sites will be monitored annually using high resolution satellites and drone imagery to track mangrove growth and survival, and in water assessments will be conducted annually for at least five years to assess changes in fish and benthic communities as well as environmental characteristics. Monitoring will include the collection of data following methods of our initial baseline data collection and application of the methods for assessing change in live mangrove cover using drone data as well as natural recruitment and/or survival of planted mangroves. Comparisons to control sites with no restoration will be used to assess changes due to restoration efforts.