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WWF technical Report

PART 1: GENERAL NARRATIVE REPORT

Project Title:	Facilitating coral reef resilience to climate-driven bleaching incidence through bioengineering as a means of lesson-learning: A continuation
Project Number:	DW50
Reporting Period:	July 1, 2020-June 15, 2021: Report 6 Final Summary of work to date
Organization Submitting Report	Fragments of Hope

Citation suggestion: Carne, L. (2021). Facilitating coral reef resilience to climate-driven bleaching incidence through bioengineering as a means of lesson-learning: A continuation. Technical Report 6. DW50. Fragments of Hope and the World Wildlife Fund.

Project Overview.

The bleaching event in 2020 surpassed the severity of any other year, with the high sea temperatures lasting from January through October. It did follow the more usual pattern (unlike 2019) because temperatures rapidly dropped in October, so there was relatively quick recovery of even completely bleached acroporids. However, because southern Belize had an early category 1 hurricane in September, Nana, which made landfall/passed through South Water Caye Marine Reserve, many of the natural acroporid stands near Placencia were affected, as well as replenished corals at LBCNP. Because the storm flipped or upended corals, bleaching was even more severe for some as their undersides were exposed to extreme temperatures and light and there was some partial mortality. While there are still no reports of SCTLD in southern Belize, it spread rapidly through the northern MPAs and because of this Fragments of Hope (FoH) again conducted a training course and installed two nurseries in Caye Caulker Marine Reserve in December 2020. Due to COVID restrictions the participant numbers were limited, with most being MPA staff from Hol Chan, Caye Caulker and Bacalar

Chico Marine Reserves, and just two private sector (tour guide) participants. The emphasis was on cement outplanting, and direct outplanting with micro-fragments. Although outplanting began in December 2020, high winds limited the number of field days throughout 2021, and a total of 5,808 corals were outplanted across four sites in southern Belize, compared to 12,162 corals across eight sites, of which 5,536 corals were outplanted in the four sites nearest Placencia in 2020. The lower numbers also reflect that several other grants/projects closed in 2020, and thus many nurseries had been harvested completely. The lower numbers also reflect a planned emphasis on micro fragmenting, and a different saw in use; FoH was unable to source their preferred saw and has tried two other types/brands sourced locally, and these saws do not allow for cutting the corals as small or as quickly as the previous brand tile saw. However, the emphasis for 2021 was also on increasing genetic diversity at each target site, versus mass quantities of corals, and this was achieved. At LBCNP, the oldest replenishment site, there are now 29 different *Acropora palmata* genets, 22 distinct *A. cervicornis* genets, and two *A. proliferas*. At Silk Caye there are now 14 *A. palmata* and 11 *A. cervicornis* genets, and at Moho Caye there are now 10 *A. palmata* and 11 *A. cervicornis* genets. None of the *A. palmata* outplanted at near-shore False Caye survived the 2019 bleaching event, but two *A. cervicornis* genets did survive both the 2019 and 2020 bleaching event, and one nearby sourced new *A. cervicornis* genet was both outplanted and added to the nurseries. The most recent (2020) diver-based mosaics reflect that just 209 outplanted *A. cervicornis* fragments in 2010 led to almost 56% live coral cover (of 59% total) ten years later at sub-site 9, and at sub-site 20 just 885 outplanted *A. cervicornis* in 2014 led to 63% cover of 65% total live coral cover in just six years (baseline coral cover prior to outplanting was 2-6%). No additional corals are placed in these quantified sub-sites. With the newly added drone orthomosaics method as a tool for quantifying larger areas than the diver based mosaics (50-200m^2), FoH could calculate that over 20% of a hectare (2,240m^2) at LBCNP was replenished acroporids in 2019, and further, one year later, coverage had increased naturally by almost ~7% to 2,397m^2 (pre-hurricane Nana). With these two powerful quantification tools, the message is clear that given the right site selection and coral selection criteria, mother nature just needs a little jump start to facilitate reef recovery. Therefore FoH's future efforts can expand to additional sites with emphasis not on large number of outplants, but on outplanting with high genetic diversity and strict coral and site selection criteria.

Progresses on each activity are listed in Section 3 below in numerical order (Activity #1-9), while Project Successes (Section 2) are listed in chronological order.

Project Successes.

Lisa Carne was an invited speaker to the online session entitled, "Solutions from the MAR" within the larger Global Coral Reef Week event scheduled in lieu of ICRS 2020. The talk is entitled "Scaling up coral restoration and measuring its success" and was live on July 10, 2020[1]. For the International Women and Girls in Science in February 2021, the Commonwealth Blue Charter released two versions (short for social media, and full length on the website) of the case study video of FoH's work at LBCNP filmed the previous November, and a PDF of the case study, both on their website[2]. Carne gave an invited talk to the Garifuna Nations' celebration of International Women's Day on March 7, 2021 entitled, "Climate Change: engaging with coastal communities in marine conservation in Belize"[3] with almost 2,000 views. Also in March 2021, Carne shared the way Fragments of Hope is using drones to quantify large areas of replenished reef for the last online lesson (3) of The Nature Conservancy's Remote Sensing and Mapping for Coral Reef Conservation[4]. This is a result of the training and collaboration with Dr. Steve Schill (TNC) since 2019. In early April 2021, the textbook "Active Coral Restoration, Techniques for a Changing Planet" was published, edited by David Vaughan, featuring FoH work at LBCNP on the cover and in chapter 11 (authored by L. Carne and M. Trotz)[5]. In early May 2021, an article on Carne and history of work at LBCNP in Belize was published by BBC's Future Planet series[6] and has already generated over US$10k in private donations. As a follow up, the journalist released the podcast with Carne and FoH US Board member Dr. Maya Trotz[7]. In early June 2021, ICRI hosted a virtual event, "Restoring Reefs: Guidelines, Best Practices and Success Stories" where FoH's work was highlighted by three different speakers[8]. Finally, the accepted ICRS 2020 abstract entitled "Challenges in evaluating reef restoration success: how long do we need? Lessons learned in Belize the past decade" was moved to ICRS 2021 virtually, scheduled for July 19-23, 2021 (Activity 9).

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[1] https://www.youtube.com/watch?v=OtuHss32iFI (starting 1:17:00)

[2] https://bluecharter.thecommonwealth.org/fragments-of-hope-community-led-coral-reef-restoration-laughing-bird-caye-national-park-belize-on-going/

[3] https://fb.watch/5QWzyOwI9E/ (starting 5:01:40)

[4] https://www.youtube.com/watch?v=DszvBUMBwo0 (Starting 29:15)

[5] https://www.jrosspub.com/science/environmental-science/active-coral-restoration.html

[6] https://www.bbc.com/future/article/20210430-the-woman-who-rescues-caribbean-coral

[7] https://veronikaperkova.com/2021/05/11/fragmentsofhope/

[8] https://www.youtube.com/watch?v=2_fv5qRmTp0 (starting 53:56, 1:11:22 & 1:23:03)

3) **Progress on Activities and related financial issues.**

Activities #1 & #2. Maintenance of over 16 nurseries in southern Belize continued, with cleaning and reinforcement of structures conducted regularly. Even the oldest tables (2009) at Whipray and LBCNP are still viable, with continued reinforcement (Figures 1d-e). False Caye tables, the newest (2017) and closest to shore, continue to require the most maintenance in terms of both fouling macro algae and rapid deterioration of nursery materials (plastic ties and grids), likely due to high nutrients and temperatures near shore, and relatively poor water quality (Figures 1a-b) compared to further away from shore sites.

Activity # 2 is adding new corals to nurseries; three 'new' *A. cervicornis* genets have been added to Silk, False, Whipray and LBCNP nurseries, and additional new genets sourced. In total, 42 new ropes were added with 449 *A. cervicornis* fragments from four different genets.

Figs. 1a-c. Comparing macro algae on tables at nearshore False Caye (top) installed 2017, versus offshore Silks Caye (bottom), installed 2015.

Figs. 1d-e. Oldest table nurseries at Whipray (L) and LBCNP (R) installed 2009; everything besides the stony coral species recruited naturally to tables. Note *Porites astreoides* recruits on the metal bar in right of Fig. 1d.

Activity #3: Monitoring of nurseries and outplants has also continued, with highlights from the effects of the hurricane (Nana category 1) and bleaching events in 2020 shown below. Despite these events, recovery at all sites except False Caye (Figures 3a-c) was fairly rapid. Figures 2a-b illustrate a large (almost 10 years outplanted) *A. palmata* flipped at sub-site 13, then bleaching completely by October 2020, but recovered with partial mortality and beginning to re-skin/re-sheet itself by March 2021. Figures 4a-b show the difference between the wind-ward side outplants at LBCNP (left) which had minimal to no bleaching (storm damaged corals being the exception) and lee-ward side where almost all the *A. palmata* colonies bleached to varying degrees. Even though nearly every outplanted *A. palmata* micro-fragment at South Silks bleached in 2020, most all recovered fully, despite being outplanted in < 1m water (Figures 5a-d); some exceptions were micro fragments most recently outplanted and extremely shallow. While these climate change related events are becoming more frequent and extreme, as has been predicted, samples were collected from multiple corals with variable but long term bleaching histories for more detailed genetics analyses; these results are still pending (and funded externally from WWF). More details on the bleaching events and results from diver -based mosaics on plots with areas 50-200m^2 at both LBCNP and Moho Caye are under Activity #5. Even larger scale outplant monitoring is under Activity #8 mapping.

Predation continues to be the main cause of outplant mortality, even more so than bleaching and storm events. While snails are easily removed and transported, fireworms sting and require tongs and a ziplock to safely remove them from the corals (Figs. 7a-b). Monitoring nurseries also includes continued collection of growth rates for *A. cervicornis* (TLE=Total Linear Extension) and three new genets (see also Table IIa under next section) were added across three different nurseries (Figure 8) but the growth rates for these new genets are only through 60 days versus

90-100 days for the previous genets; the larger the fragments grow/longer they are in the nursery the higher the averaged growth rates become as more new apical branches form.

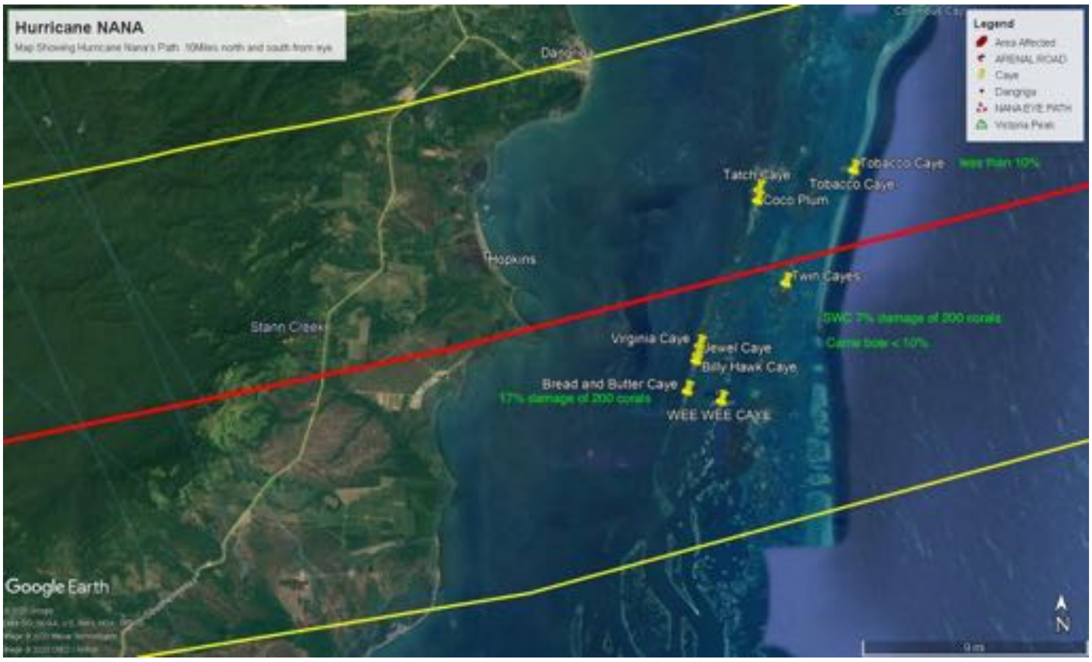
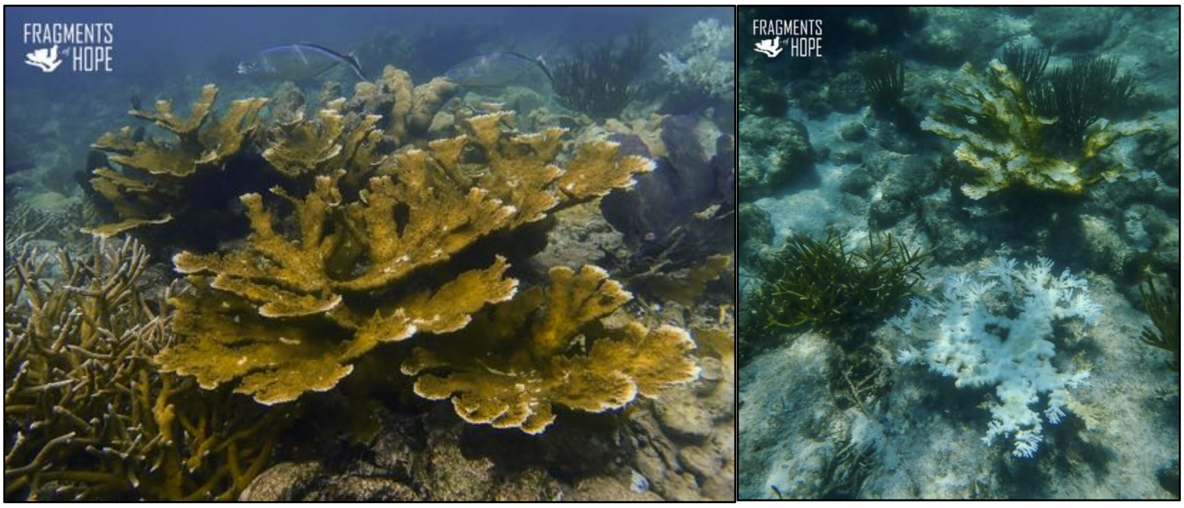


Fig. 2. Hurricane Nana made landfall September 4, 2020. Affects were seen as far south as LBCNP on both natural and replenished sites.

Figs. 2a-c. Hurricane flipped a large outplanted elkhorn at sub-site 13 that had ~ 10 years on the reef. Because the undersides of many flipped corals were exposed to extreme temperatures and light, there was some partial mortality on many colonies that survived the 2017 & 2019 bleaching events. In most cases, there was not full mortality, and the corals are recovering.

Fig. 3a-c. Outplanted *A. prolifera* at False Caye survived the 2019 bleaching event but was 'wholly' bleached with partial mortality in October 2020 (L) and did not survive (middle photo from December 2020); one of two *A. cervcornis* genets did survive at False Caye (R), photo from December 2020. Heavy macro-algae at False Caye is an indicator of high nutrients at this near-shore site.



Figs. 4a-b. Five and half year old outplanted corals on the windward side of LBCNP did not bleach at all, photo from late October 2020 (L) versus many on the leeward side of LBCNP, photo from November 2020 (R) with different degrees of severity and recovery rates.

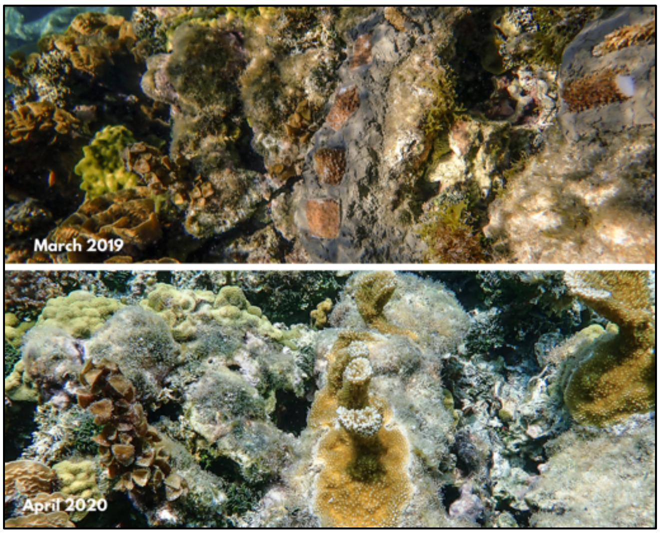
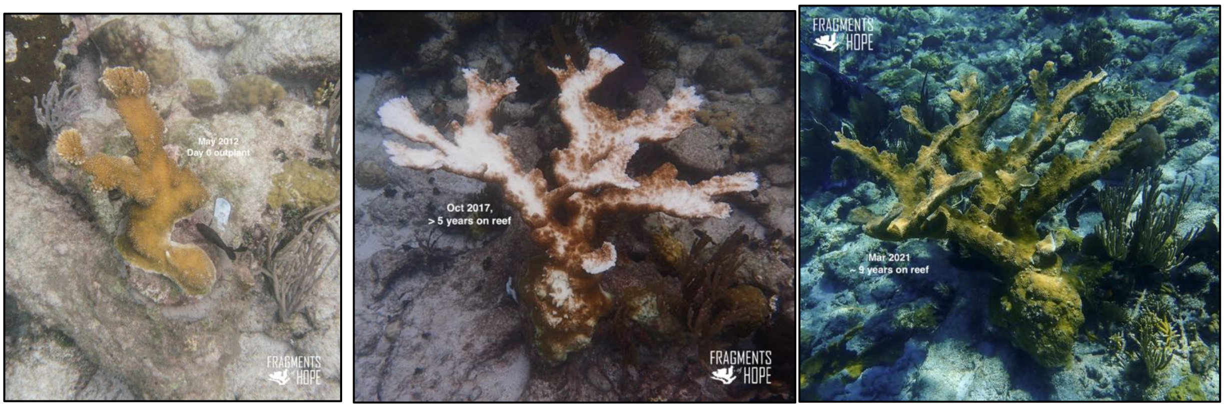


Fig. 5a-d. Top two images are *A. palmata* micro fragments directly outplanted on the shallow fringing reef at S. Silk Caye Day 0 (top) and 13months later (bottom). Bottom three images show full bleaching in October 2020, but full recovery by December 2020, and thriving in May 2021 (two years outplanted).



Figs. 6a-c. Time series of an outplanted elkhorn at LBCNP sub-site 18 2012-2021:this coral bleached 2017, 2019 and 2020 but fully recovered (<5% partial mortality).

Figs. 7a-b. Predation is still the highest cause of outplant mortality, pictured are macro shots of the fire worm engulfing outplanted *A. cervicornis* at S. Silk Caye.

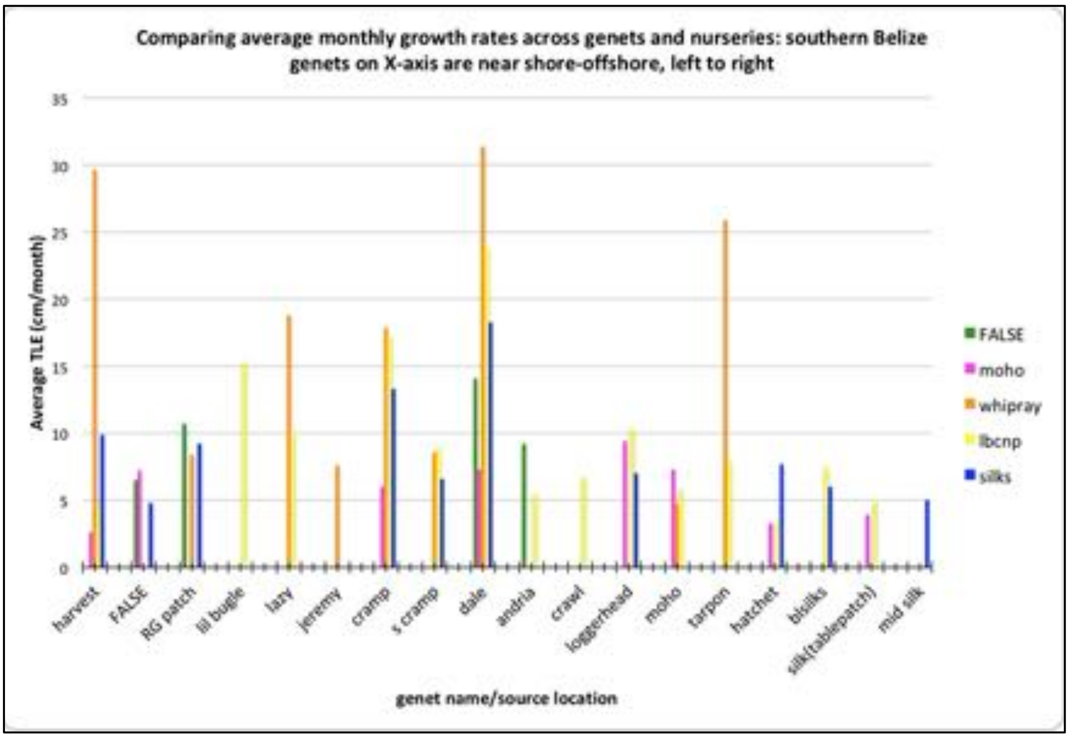


Fig. 8. Total Linear extension (TLE) growth rates (averaged at cm/month) for 18 different *A. cervicornis* genets across five different nurseries sites. The three new genets are RG patch, Jeremy and S Cramp Caye. The genets are named for their source location and shown left to right, near shore to offshore on the X axis.

<u>Activity #4: Outplanting</u>

Although outplanting began on time (December 2020-May 2021) as opposed to the previous year when bleaching lasted abnormally long, the total numbers of corals outplanted for 2021 is the least amount of the last three years (Tables Ia-c) for several reasons. First, the number of corals in the nurseries had been reduced due to closing several other grants/projects in 2020 (only the numbers for southern sites are shown, FoH really outplanted > 12,000 corals in 2020 across Belize); without secured funding one of the risks to adding many corals is overweighted or neglected nurseries. Secondly, the emphasis was meant to be on micro fragmenting and direct outplanting however due to the SCTLD spreading though Belize, only acroporids were outplanted this past season, and the preferred type/brand/model of tile saw was not replaceable in country therefore the team had to work with saws available in Belize that are both unable to cut smaller pieces and also cut much slower than the preferred brand/model (Figs. 10a-d). However, the real limiting factor was weather: from January-May 2021 FoH only managed four-five field days each month due to excessively high winds, and of those days, a smaller fraction were appropriate weather for outplanting with cement. Despite these constraints, 5,808 coral fragments (5,039 *A. cervicornis* and 769 *A. palmata*) were outplanted across four sites: Silks (Figures 9d,10a-d, 11a-b), Moho, LBCNP and False Caye (Figs. 9a-c). Genetic diversity was enhanced for *A. cervicornis* and *A. palmata* (tables IIa-b) at most outplant sites, and additional *A.*

cervicornis genets were added to nurseries at LBCNP and Silks (*X*'s in italics in Table IIa reflect that they have not yet been outplanted, so are not included in total genets), and the Whipray genets/nurseries are not shown in Table IIa.

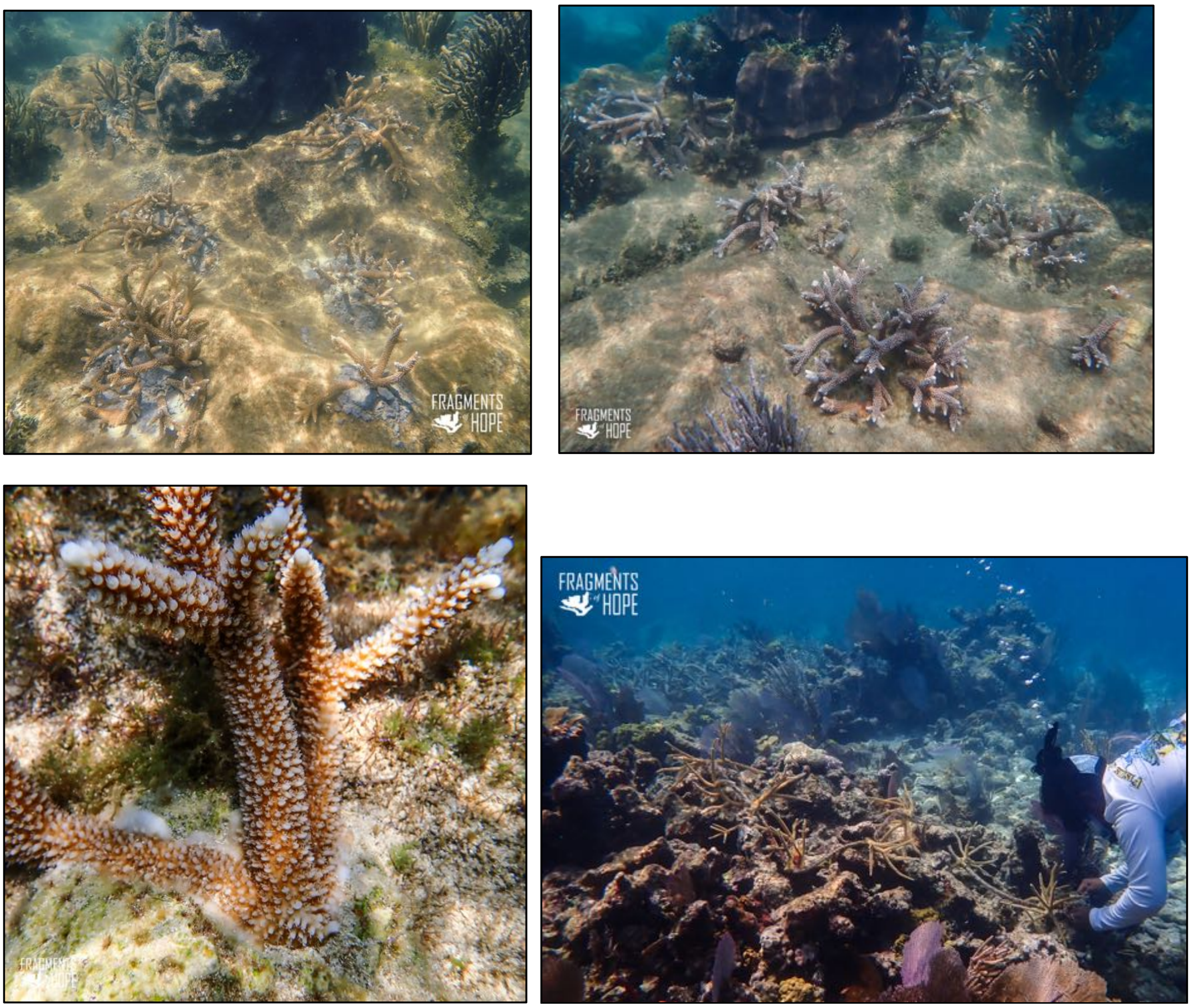
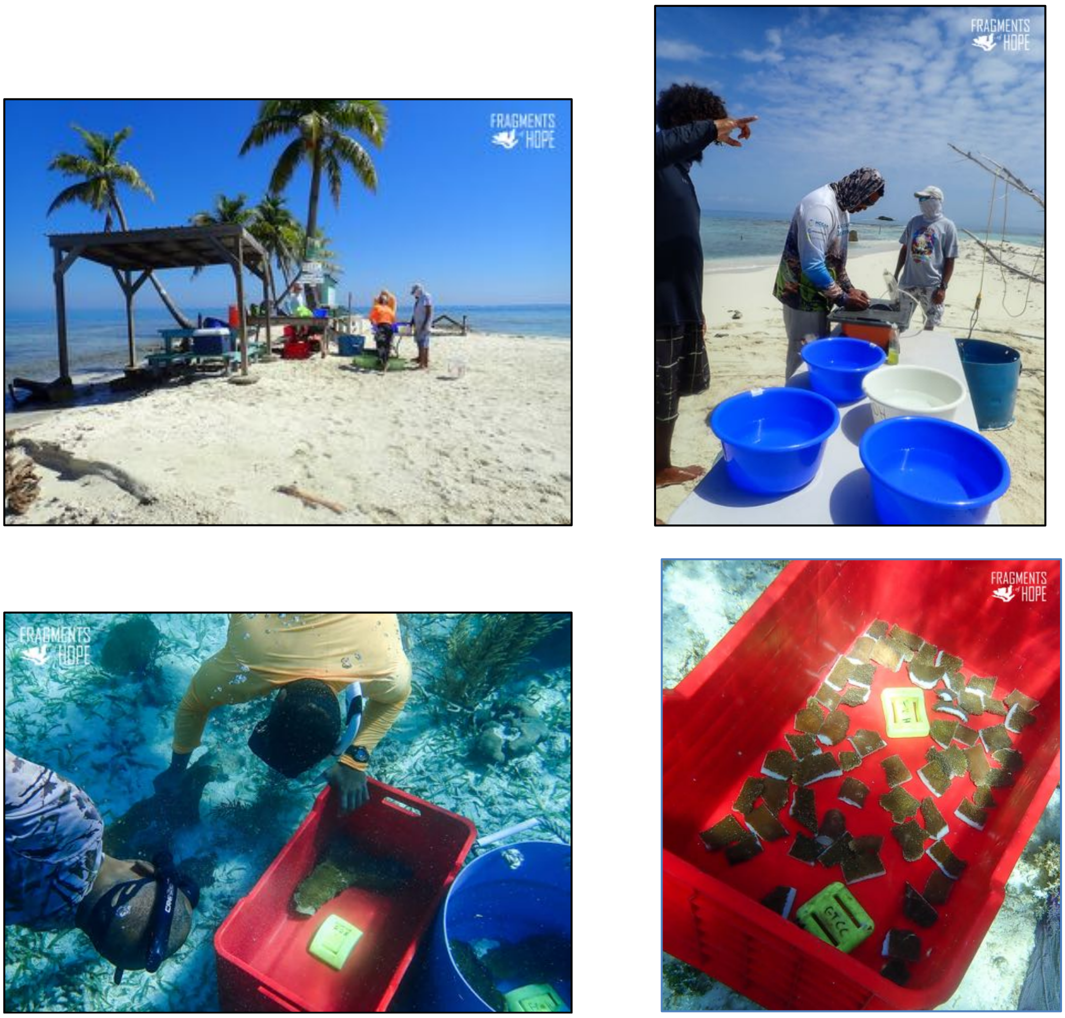
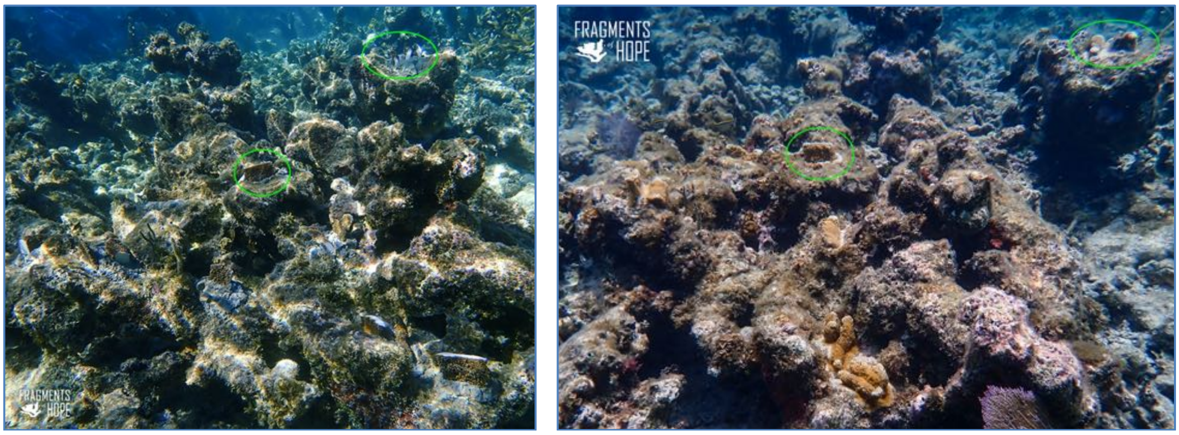


Fig. 9a-d. From top left, clockwise: (a) day 0 outplanted new *A. cervicornis* genet with cement at False Caye 17Mar21 (b) 48 days later and (c) close up of growth onto substrate/reef after 48 days (d) outplanting *A. cervicornis* entire ropes with nails at S Silk Caye 19May21.



Figs. 10a-d. From top left, clockwise: (a) During COVID with no tourists FoH could use the shade on the small S. Silk Caye for micro-fragging but once tourism opened up FoH had to use Middle Silk Caye, with no shade, and bring their own table (b); collecting (c); the smaller wet tile table saw, sourced in Belize, cuts slower, and larger pieces than the saw used 2017-2020 (b & d).



Figs. 11a-b. Day 0 of outplanting micro-fragged *A. palmata* at S Silks (6Jan21) (L) and four months later May 2021 (R). Two sets of *A. palmata* circled for reference in both images.

Table Ia-c. Number of coral fragments outplanted by taxa, across southern sites near Placencia only, and separated by year (2019 -2021). ACER=*Acropora cervicornis*, APAL=*A. palmata*, APRO=*A. prolifera*, DCLY=*Dendrogyra cylindrus*, OFAV=*Orbicella faveolata*.

SITES	TAXA outplanted 2019				TOTAL 2019	TOTAL
	ACER	APAL		APRO		
LBCNP	1,905				1,905	82,879
SILKS	801	1,114			1,915	12,695
MOHO	267	597			864	18,750
FALSE	129	345		2,401	2,875	5,037
TOTAL					**7,559**	119,361

SITES	TAXA outplanted 2020				TOTAL 2020	TOTAL
	ACER	APAL	DCLY	OFAV		
LBCNP	2,859	312 (303 micro frag	0	0	3,171	86050
SILKS	0	675 (micro frags)	0	0	675	13370
MOHO	979	562 (micro frags)	30 (micro frags)	25 (micro frags	1,595	19784
FALSE	95	0	0	0	95	5132
subtotal	3,933	1,540	25	30	5,528	
TOTAL					**5,536**	124,336

SITES	TAXA outplanted 2021		TOTAL 2021	TOTAL
	ACER	APAL		
LBCNP	1052	165	1217	87,267
SILKS	626	330	956	14,326
MOHO	2572	274	2846	22,630
FALSE	789		789	5,921
subtotal	5039	769	5808	
TOTAL			**5,808**	130,144

Table IIa. Number and source location of *A. cervicornis* (ACER) genets/individuals at each of three outplant locations in southern Belize: Moho, Laughing Bird and South Silk Caye.

	Outplant locations		
genet source ACER	Moho	LBCNP	Silks
saddle	X	X	
lazy	X	X	X
gladden buoy		X	
gladden pillar patch		X	
tarpon	X	X	X
whipray	X	X	X
glens bank		X	
loggerhead	X	X	X
moho	X	X	
FALSE	X	X	X
harvest	X	X	X
hatchet deep	X	X	X
mid silks	X	X	X
bl silks		X	X
cramp	X	X	
crawl	X	X	X
andria	X	X	X
dale's reef	X	X	
lil bugle		X	
LBCNP		X	
Jeremy patch	X	X	
RG patch			*X*
south cramp caye	X	*X*	*X*
Total *A. cervicornis* genets	**16**	**21**	**11**

Table IIb. Number and source location of *A. palmata* (APAL) genets/individuals at each of three outplant locations in southern Belize: Moho, Laughing Bird and South Silk Caye.

	Outplant locations		
genet source APAL	Moho	LBCNP	Silks
gladden buoy	X	X	
gladden pillar patch	X	X	X
gladden crest	X	X	X
loggerhead1	X	X	X
loggerhead2	X	X	X
bugle		X	
larks	X	X	
larks2	X	X /X	X
s silk caye s			X
s silk caye n			X
middle silk caye1			X
midddle silk caye2			X
nursery patch silks1			X
nursery patch silks2			X
nursery patch silks3			X
french louie	X		
Mosquito caye1		X	
mosquito caye2		X	
mosquito caye 3		X	
17 genets from 2006		X	
south cramp caye	X		
loggerhead patch	X		
BL silks patch			X/X
Total *A. palmata* genets	**10**	**29**	**14**

Activity #5 Bleaching, Photo-mosaics, and fish surveys

Bleaching and Temperature Data

Sites near Placencia have been monitored for bleaching for over a decade, and the near shore sites had more severe bleaching results in 2020 than in any previous year, with the exception of two sites (Bugle and Larks, Fig. 12a), however 2020 sea temperatures dropped dramatically, quickly, in early-mid October (see Figs.12b and 13a-d), allowing relatively ‘normal’ recovery of corals by December 2020 (see Figs. 5a-d) despite the severe bleaching (Figure 12c). Figure 12d includes data from Port Honduras Marine Reserve (PHMR) as FoH assisted TIDE, along with all other southern sites comparing October 2017 through October 2020. All sites are labeled in the map in Figure 14a.

FoH has large sets of *in situ* temperature data-in some sites up to ten years, which makes it difficult to illustrate all the data at once in Excel. Dr. Colleen Bove, now a Postdoctoral Associate Lecturer at Boston University, has re-worked almost all of FoH’s *in situ* temperature data sets using the software “R”[9]; a few examples are shown in Figures 13b and 13d-e. Figure

[9] https://www.r-project.org/about.html

12b is NOAA data, courtesy Dr. Mark Eakin, through October 2020 and illustrates both sea surface temperatures from satellite data (top lines) with 2020 in black, and Degree Heating Weeks (DHW)[10] on the lower part of the figure, with 2020 also in black. This data is from the virtual monitoring station at Glover's Reef and shows the ten hottest years in Belize, not just the last ten years.

Figures 13a and c are a sample of some of FoH temperature data from multiple sites comparing different years and/or different locations. FoH has temperature loggers in each nursery and many outplant site locations. The prevalent trend across all sites, is the higher temperatures throughout most of 2020, then the sudden drop in temperature early-mid October, compared with 2019 that had an unusually late temperature peak in October which caused bleaching to last many months longer than in the 2020 bleaching event. Each graph/map is captioned with details.

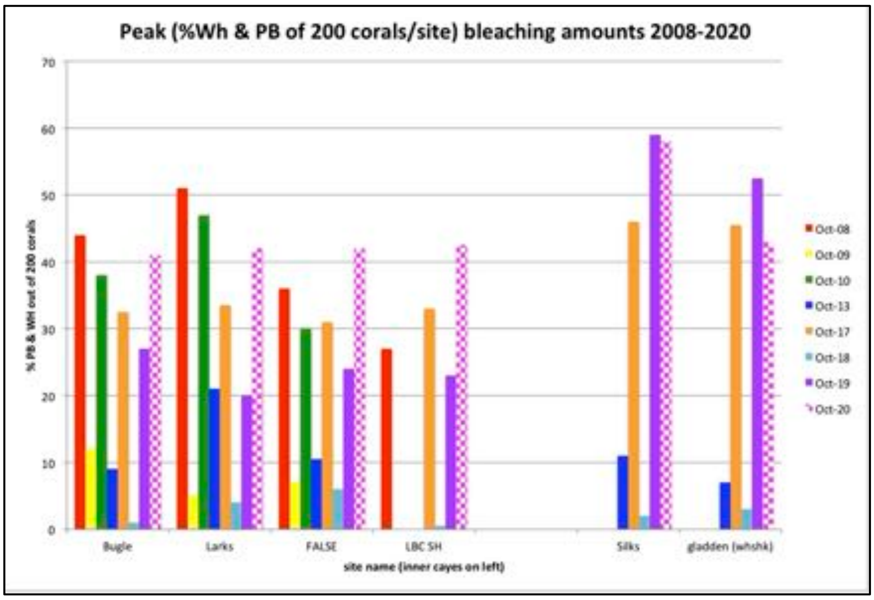


Fig. 12a. Comparing bleaching rates in October 2008-October 2020 (where data available) at multiple sites (X-axis) in southern Belize. All are sites are shallow (1-5m), From left to right is near-shore to offshore, see labeled sites on map in Fig.14a. The percentage of bleaching (Y-axis) is based on 200 corals per site surveyed. "Pale" corals are not included.

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[10] https://coralreefwatch.noaa.gov/satellite/methodology/methodology.php#dhw

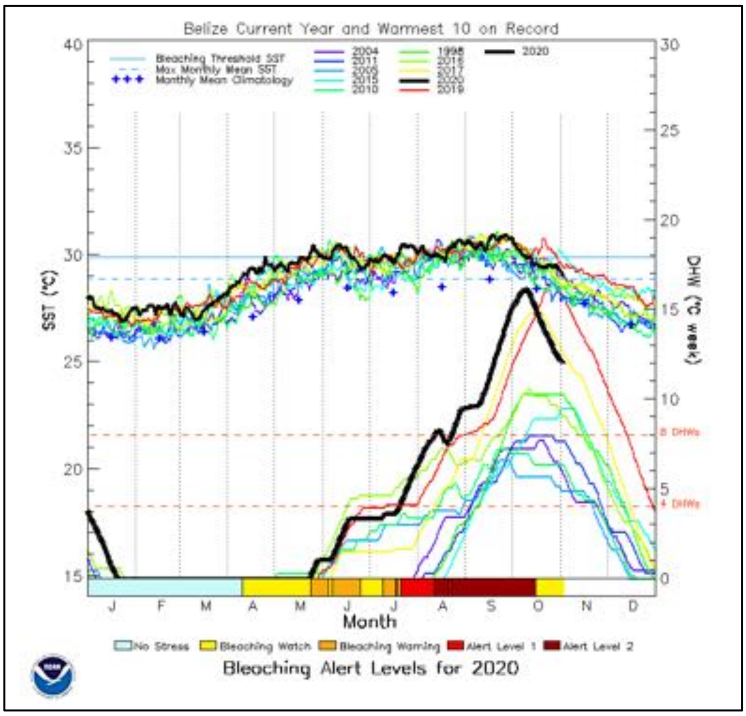
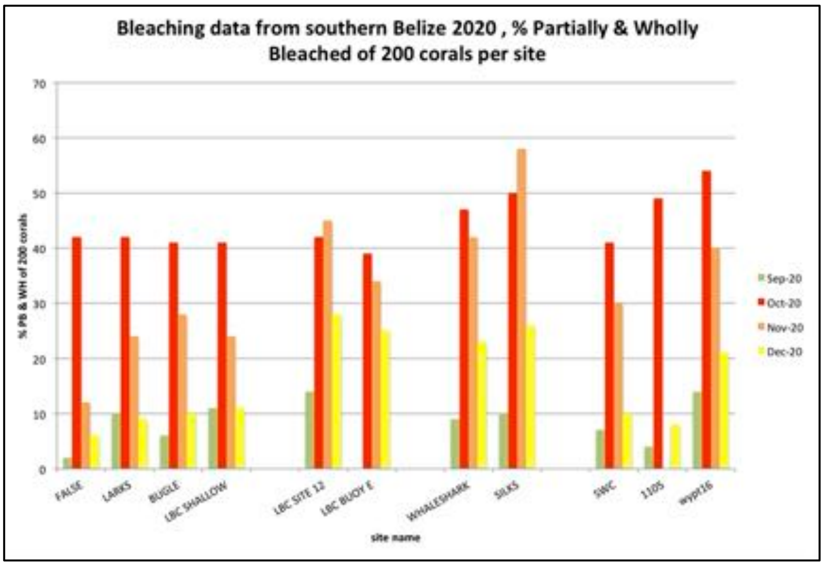


Fig. 12b. Data (satellite sea surface and DHW) from NOAA illustrating the ten hottest years for Belize, with 2020 in black and surpassing all other years in temperature until early-mid October 2020.



Figs. 12c. Bleaching data for 2020 only (September-December) at FoH regular monitoring sites in southern Belize (from left to right on x-axis is near shore to offshore, LBC site12, LBC Buoy E and wypt 16 are fore reef sites ~ 14m deep, all others are 1-5m).

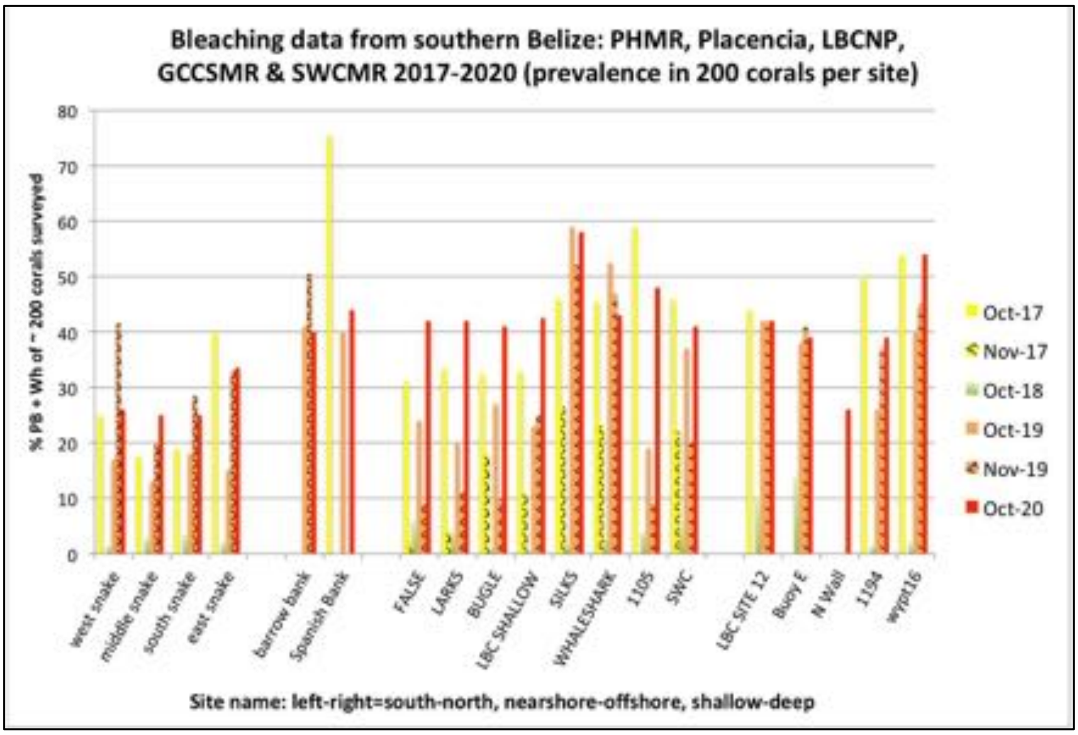


Fig. 12d. Bleaching data October 2017-October 2020 including PHMR sites (see map in Figure 14a for site locations).

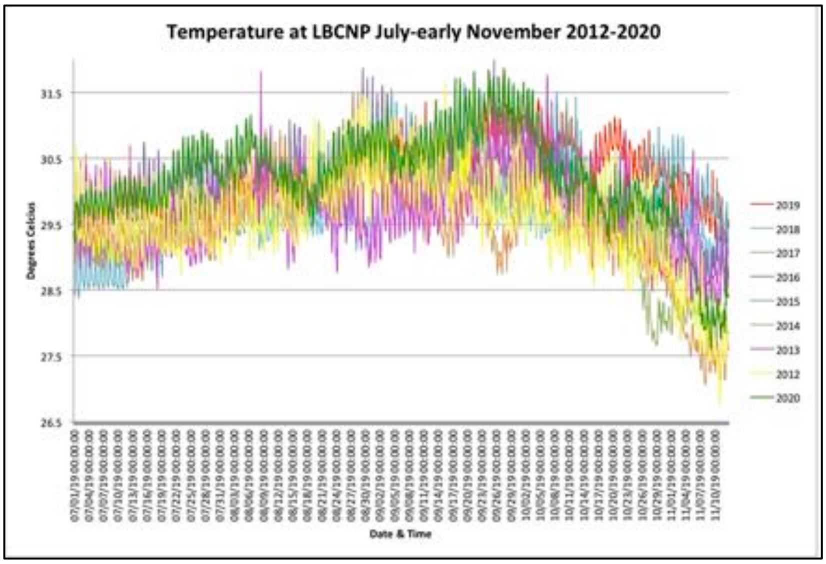


Fig. 13a. LBCNP is a site where > 10 years of temperature data exist; here only 2012-2020 is shown and 2020 is in bright green, showing the elevated temperatures throughout the year versus previous years until October. The logger is located on the west side of LBCNP ~ 5m.

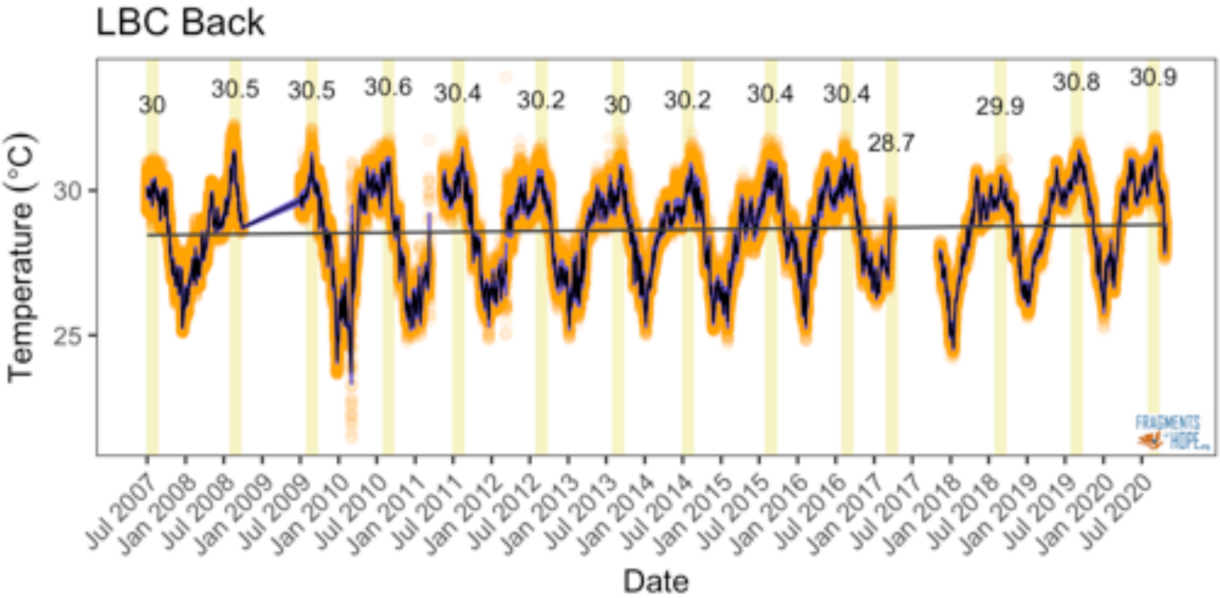


Fig. 13b. This is all the *in situ* LBCNP temperature data analyzed in "R" by Dr. Colleen Bove. This is raw observations in orange, the daily mean in black, with the 95% confidence in purple and a trend line added.

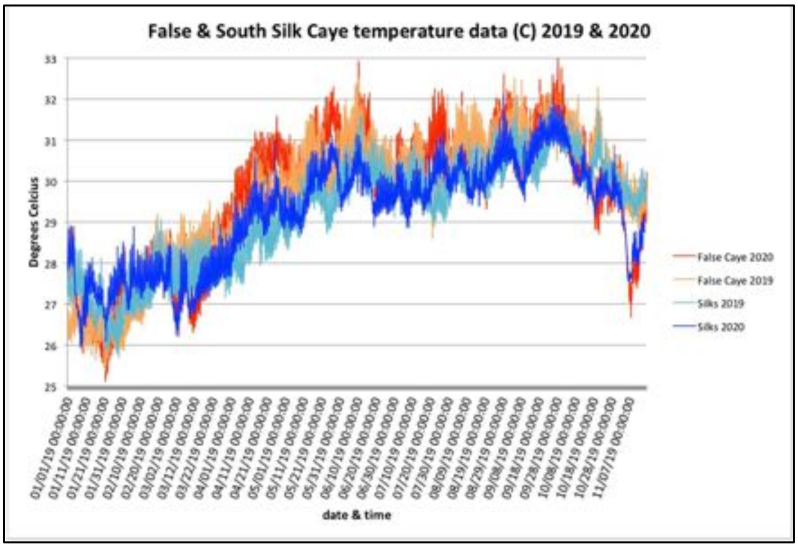
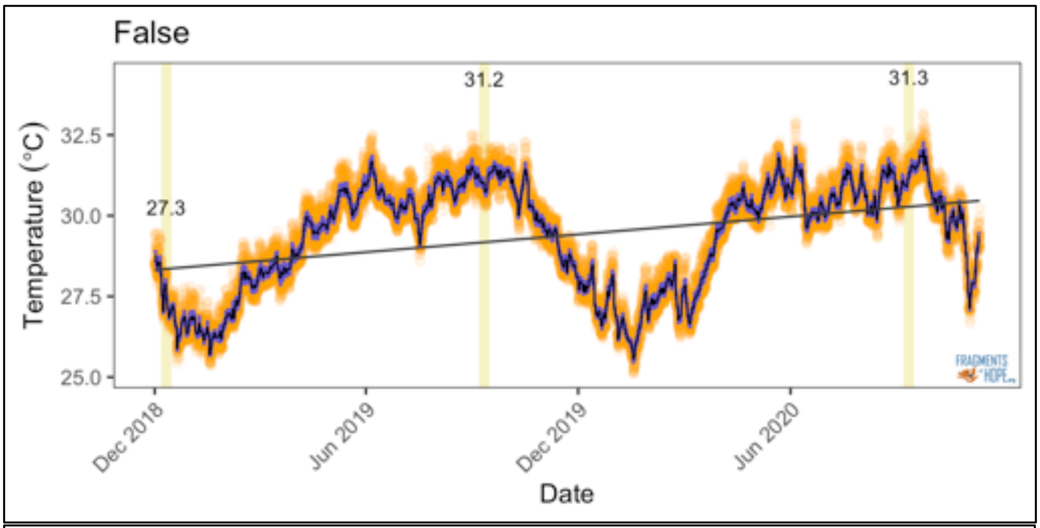
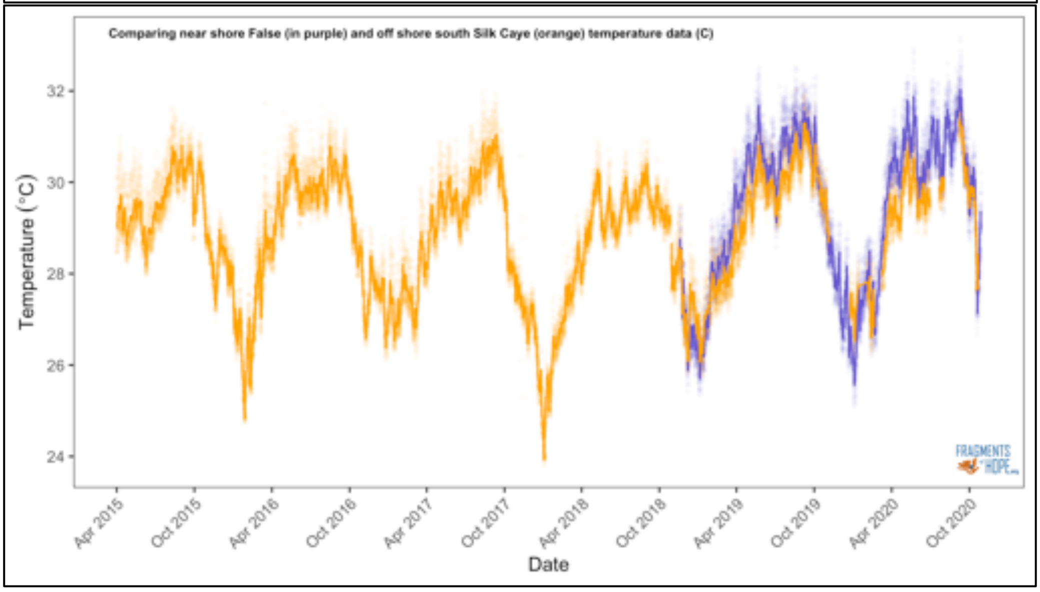
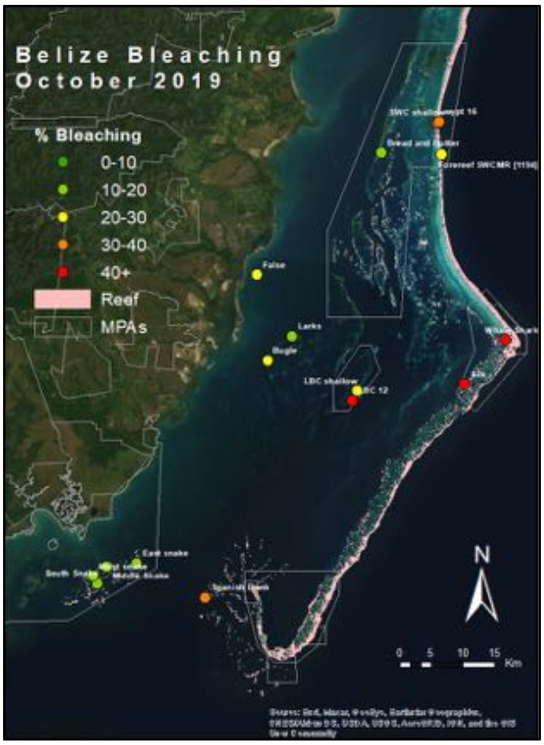


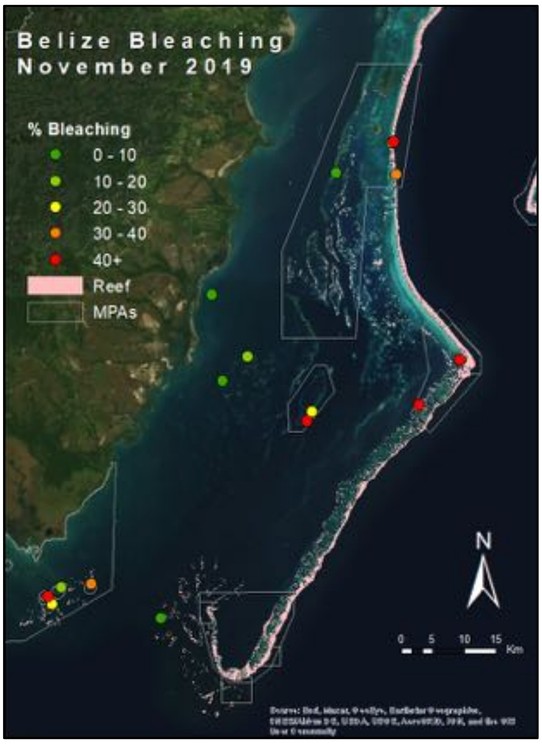
Fig. 13c. This graph compares temperature data for two years (2019 and 2020) at two extreme locations, Silks on the outer reef (light and dark blue line) and False Caye near shore (orange and red lines). The locations are shown on the map in Fig.14a and also, the corals took longer to recover at Silks (offshore) than at False (near shore) despite both sites having initially equally high bleaching prevalence in 2020 (Fig. 12c). However, the acroporid outplant mortality at False Caye (Figs. 3a-b) far exceeded that at Silks Cayes (Figs. 5a-d), which was minimal in both years.





Figs. 13d-e. The top graph shows temperature data at False Caye using "R", analyzed by Dr. Colleen Bove. This is raw observations in orange, the daily mean in black, with the 95% confidence in purple and the trendline showing a clear increase. The bottom graph compares temperature data from Silks (offshore, in orange) and near shore False (in purple). This the same temperature data used in Fig 13c but using a different program, with the actual raw observations in lighter color and the averaged in the bolder color lines.





Figs. 14a-b. Maps of sites surveyed for bleaching (2017-2020) with labels on the left. These maps are October and November 2019, showing the peak bleaching came later for many sites than usual (October) in 2019; prevalence (% corals bleaching of ~200 surveyed per site) are color coded. This also reflects severity of bleaching as no “pale” colonies are included.

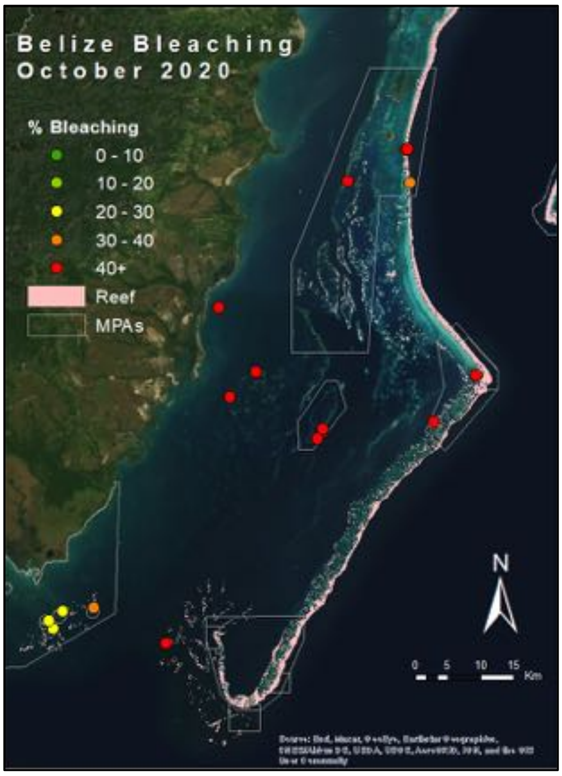


Fig. 14c. In 2020 the peak bleaching was in October (normal peak time) but 2020 stood out as the worst beaching event in Belize to date. Prevalence (% corals bleaching of ~200 surveyed per site) are color coded. This also reflects severity of bleaching as no “pale” colonies are included.

Diver-based mosaics

Seven years of diver based mosaics at LBCNP now finally reveal a pattern: the largest yearly increase in coral cover was after ~3.5-four years on the reef: in 2018 for sites 24, 23, 20 and 21 (blue bars) and in 2015 for site 13 (outplanted in 2010, far right, Fig. 15). Table III lists outplant dates, locations and details, and this data implies the density of the outplants (2-38 frags/m^2) seems not to correlate with increases of coral cover; instead site selection and coral selection plus patience may be key to replenishment success. FoH *A. cervicornis* growth data from Turneffe and South Water Caye Marine Reserve indicate corals sourced and growing in southern sites near Placencia have up to double the growth rates as the northern corals/sites. Therefore these types of results may take 6-10 years in other locations. Figure 15a illustrates the total live coral cover at each LBCNP sub-site 2014-2020, and Figure 15g is data from three sub sites at Moho Caye 2015-2010. All three sites at Moho were unplanted in 2015, whereas only two sites at LBCP (23 and 24) were unplanted in2 014, when the diver based mosaics began.

There are some limitations and subjectivity to using the open source software CpCE: for example categories of rubble versus dead reef, identifying CCA, and there are only vague categories of "sponge"-at least encrusting vs upright would be useful. Most of the sponge in all the mosaics are the *Clionid spp*. the brown encrusting sponge (see Figure 15h for comparing benthic community changes over time at a single unplanted site at LBCNP and the average of three unplanted sites at Moho Caye). Likewise 'gorgonian' reflect several different species. This data warrants much more thorough analysis and ideally by multiple persons to eliminate any bias. Because all increases in live coral cover are form the replenished acroporids totals are shown, and not broken down by the few different corals species on sites. Figures 15b-f are the processed diver based mosaics for the unplanted sub-site 24 at LBCNP and help to give a visual- the lasts drop (not 2016) in coral cover from 2019-2020 reflects some collapse of the large *A. palmata* colonies on this, the smallest of quantified sites (~40m^2).

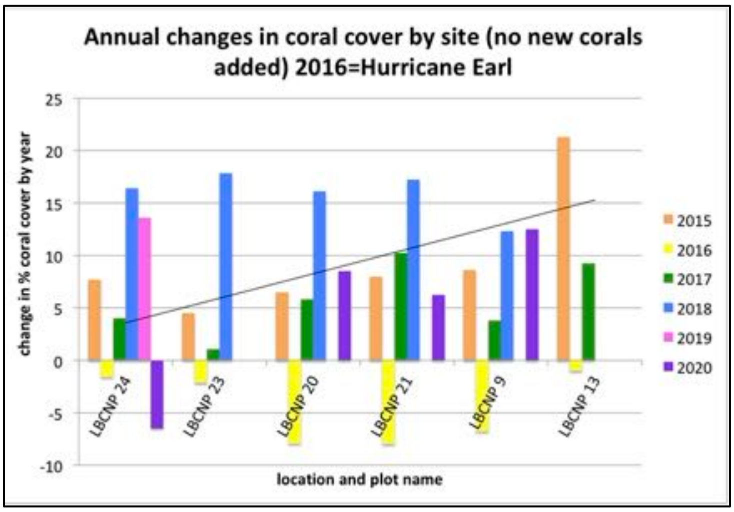
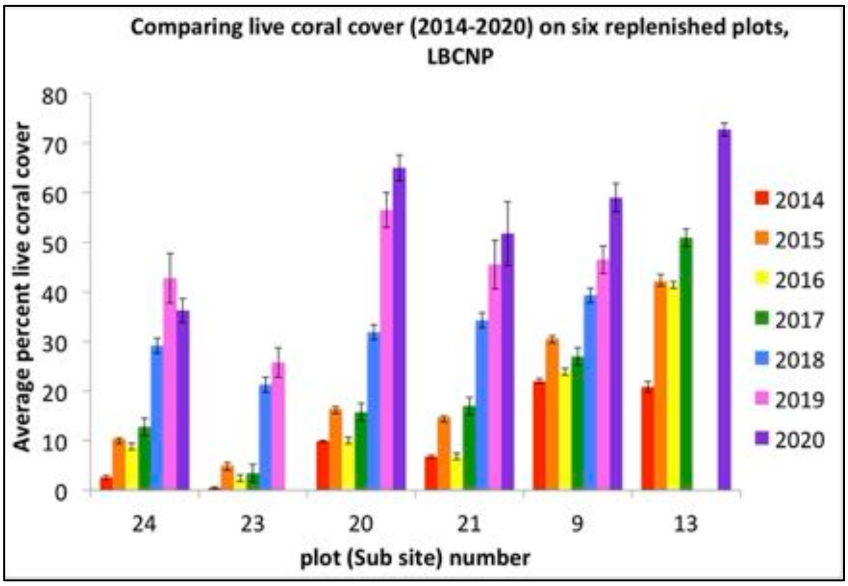


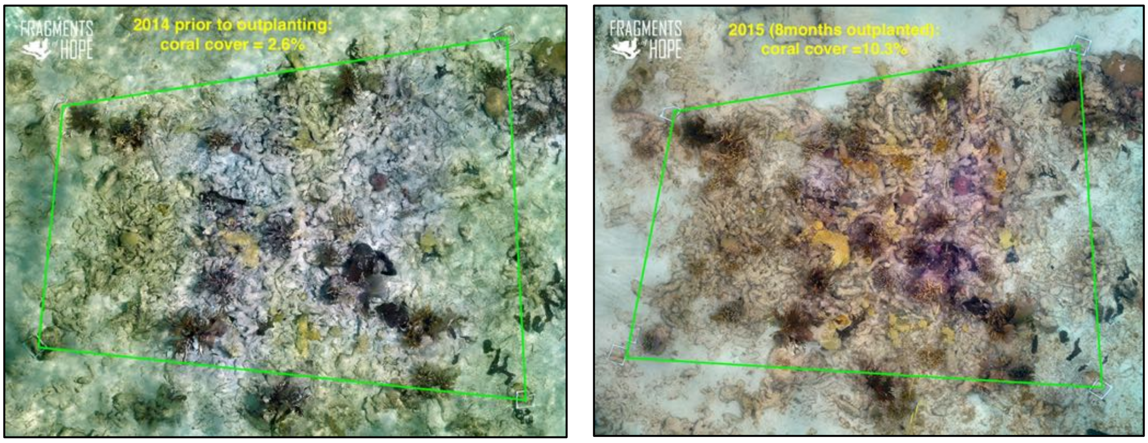
Fig. 15. Shown are the yearly changes in live coral cover, where data available, from six diver based mosaics plots at LBCNP. Sites on the X-axis are from youngest to oldest, left to right. No site had any corals added after initial outplanting, dates and details in Table III. Sites were surveyed post-Hurricane Earl in 2016.

Table III. Details on each sub-site/plot at LBCNP including area (m^2), date outplanted, number of species/taxa outplanted and the latest available date percentage of acroporids from total live coral cover, using CpcE to annotate processed diver-based mosaics.

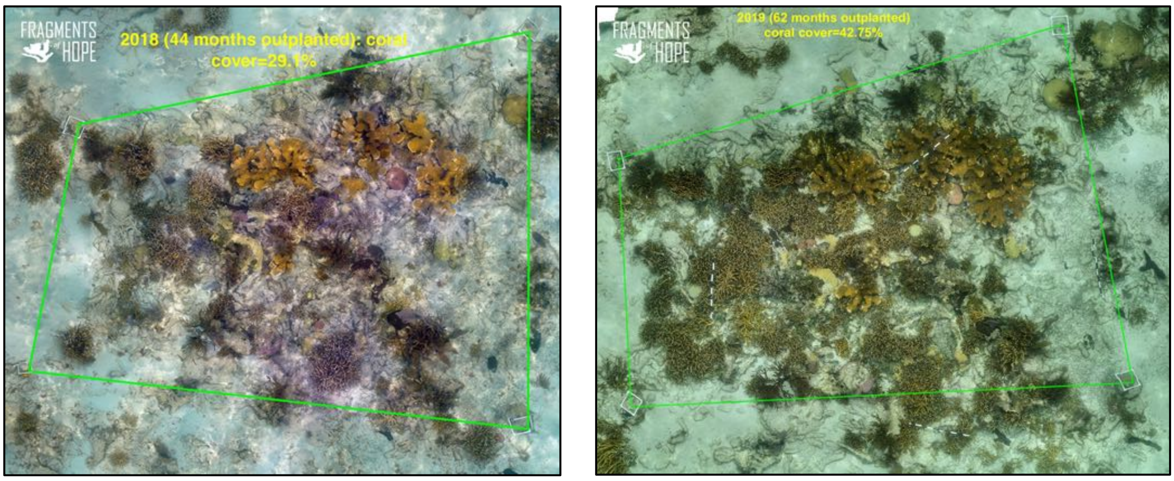
Sub-site/ plot name	Area (m^2)	Out-plant date	Species & # frags out-planted	% acroporid coverage of total live coral
13	182	12-2010	633 ACER, 3 APAL, 100 APRO (or 4frag/m^2)	48% of 51% (2017)
9	110	04-2010	209 ACER (or 1.9frag/m^2)	56% of 59% (2020)
20	144	02-2014	885 ACER, 19 APAL (or 6.3frag/m^2)	63% of 65% (2020)
21	109	02-2014	906 ACER, 11 APAL, 21 APRO (or 8.6frag/m^2)	47% of 51% (2020)
23	112	11-2014	461 ACER, 7 APAL	N/A (yet)
24	40	11-2014	1138 ACER, 12 APAL (or 28frag/m^2)	33% of 36% (2020)



Figs. 15a. Graph comparing change in total live coral cover on six replenished sub-sites at LBCNP 2014-2020, with standard error bars. The sub-sites on the X-axis are from youngest to oldest (L-R); only sub-site 24 and 23 were unplanted in 2014. Sub-sites 20 and 21 were ~ 8 months outplanted in 2014, and sub-sites 9 and 13 were ~ 3.5 years outplanted in 2014. No additional corals were added to any of these sites; the drop in 2016 (yellow) reflects the surveys being conducted just after Hurricane Earl (category 1) in Aug 2016. The sites in 2020 were surveyed prior to Hurricane Nana (category 1) in 2020, except for sub-site 13 (far right) which was repeated in October 2020.

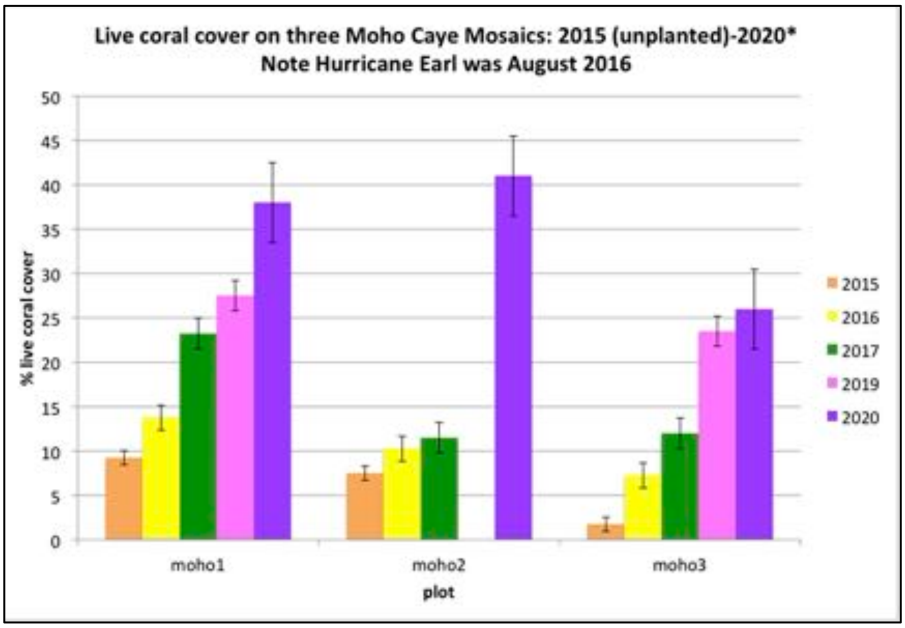


Figs. 15b-c. The fully processed diver based photo-mosaics on sub-site 24 2014 (unplanted) and 2015 (8 months outplanted).



Figs. 15d-e. The fully processed diver-based photo-mosaics on sub-site 24 2018 (44 months outplanted) and 2019 (62 months outplanted).

Fig. 15f. The fully processed diver-based photo-mosaics on sub-site 24 in 2020 showing a slight decrease in coral cover not from Hurricane Nana, but from other storm events that affected the *A. palmata* (compare top right corner of plot to Fig. 15e).



Figs. 15g. Data from diver-based mosaics at Moho Caye 2015-2020; all three plots were unplanted in 2015 (orange).

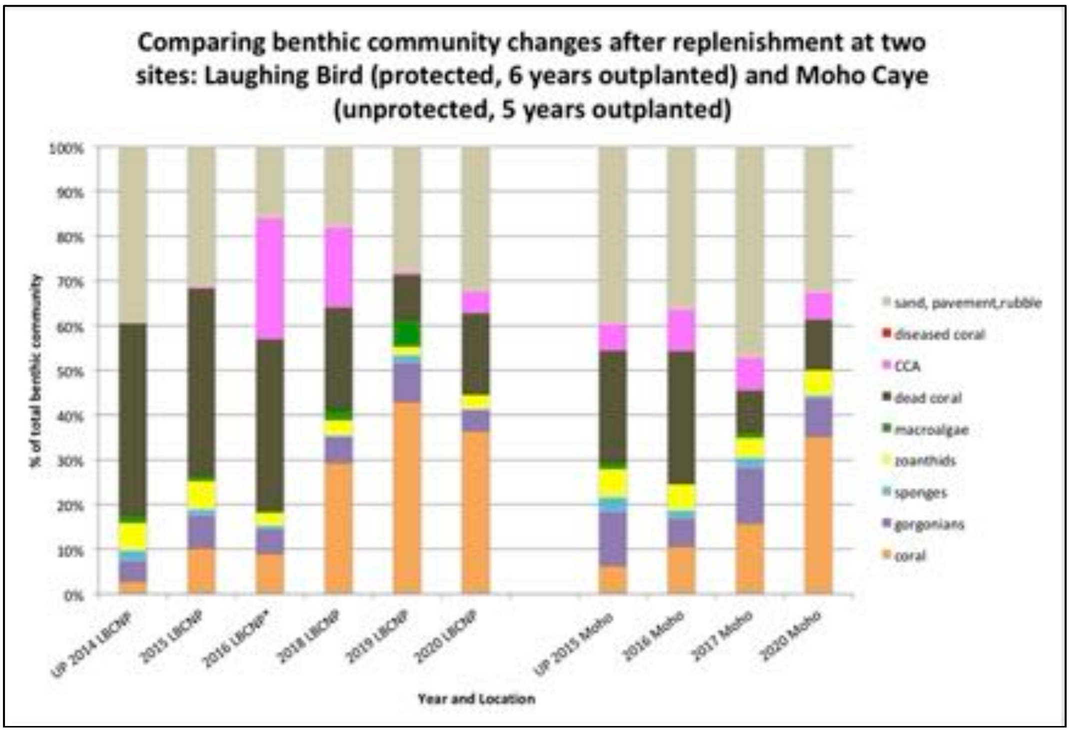


Fig. 15h. Comparing changes in general benthic community categories from a single unplanted plot at LBCNP (sub-site 24 over six years) versus three unplanted plots (averaged across three plots) at unprotected Moho Caye over five years. Hurricane Earl (category 1) was in August 2016. All 2020 diver-based mosaics were conducted pre-Hurricane Nana (category 1, September 2020).

Activity #6 Recruits and training.

In December 2020 FoH followed up in Northern Belize with more formal training in outplanting techniques. Because of COVID restrictions, only six participants from the three northern MPAs (Bacalar Chico, Hol Chan and Caye Caulker Marine Reserves) could attend, including two private sector persons, however formal certificates of completion were also issued to two additional Placencia tour guides, Natasha Gibson and Amir Neal. Ms. Gibson ad Mr. Neal have been working with FoH for over two years but were unable to attend the 2020 training formal training due to participant number restrictions.

Figs. 16a-b. The group training in Northern Belize, December 2020 (L) and N. Gibson receiving her certificate back in Placencia (LBCNP).

<u>Activity #8.</u> Mapping

Figure 17a illustrates sub-site 13 at LBCNP, outplanted in December 2010. The border lines for the diver-based mosaics are illustrated (~180m^2). The image was taken late October 2020, post-Nana and during the bleaching event; one large *A. palmata* to the right of the sub-site flipped in Hurricane Nana and bleached (Figs. 2a-c), however in general, the wind ward (east) side of LBCNP's replenished acroporids did not bleach (Fig. 4a). But what the photo really shows is that diver-based mosaics alone do not capture the extent of the replenished reef cover: the six sub-sites at LBCNP total < 700m^2, whereas the new method of using drones for shallow reef coral cover quantification allows a much greater area coverage ~ one hectare (Figure 17b-c). Figure 17b illustrates the quantification of the replenished acroporids at LBCNP from the 2019 ortho-mosaic color coded by taxa: orange =ACER 1938m^2, red=APAL 250m^2, yellow=APRO 52m^2 totaling 2,240m^2 of acroporids. Figure 17c shows one year change detection at LBCNP where the total acroporid coverage increased to 2,397m^2 (pre-Nana[11], ortho-mosaics conducted in August 2020), an increase of 7% in acroporid cover by *natural processes* (although some outplanting did occur at LBCNP between drone flights, most were micro-fragments which are not detected by the drone).

FoH also began mapping natural acroporid stands in late 2019 through 2020 and classified in total, > 7,900m^2 of reef at replenished sites LBNCP & Moho, and five natural acroporid stands near Placencia. Examples in Figure 18a show yearly change detection (2019-2020) at a natural acroporid stand (predominantly *A. cervicornis* but all three acropora taxa are present) of almost ~40% increase at a site near Loggerhead Caye near Placencia. A drone ortho-

[11] A follow up drone flight/ortho-mosaics was made in October 2020 post-Nana and during bleaching but has not yet been analyzed/quantified.

mosaic was created and annotated for this site in October 2020 (Figure 9b) post-Hurricane Nana and during the bleaching event. While the *A. palmata* and *A. prolifera* coverage was reduced due to both mechanical damage and/or mortality from bleaching, the *A. cervicornis* coverage increased, as can happen with relatively minor disturbance events, as the acroporids are adapted to spread asexually via high wave energy events. But these numbers will need to be revisited/ground-truthed to verify recovery post-bleaching in 2020.

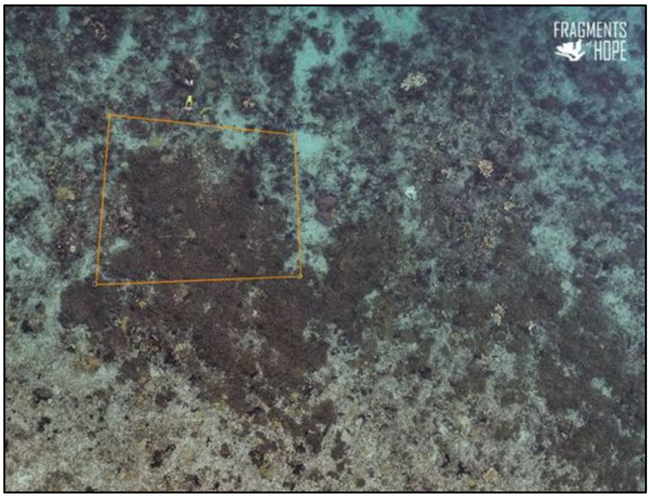
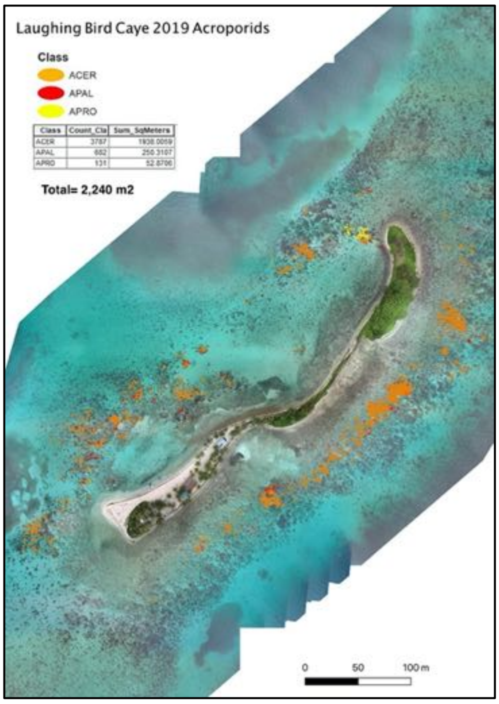


Fig. 17a. Image captured from drone illustrating a diver conducting a photo-mosaic on sub-site 13 in October 2020. The sub-site plot is outlined (~180m^2), showing clearly replenished coal coverage extends far beyond the perimeter of sub-site 13.



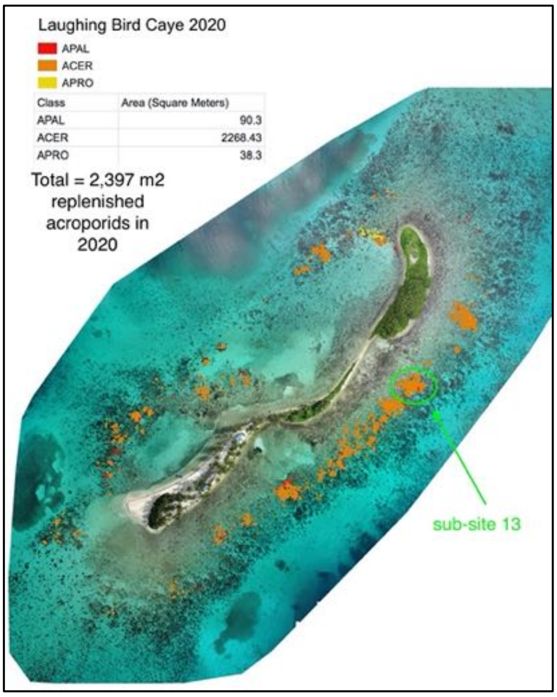


Fig. 17b-c. Example of one year (August 2019-2020) change detection in replenished acroporid cover at LBCNP using ortho-mosaics made with drones and quantified with Q-GIS. There was an increase of acroporid cover by 157m^2, which is attributed to natural spread & reproduction, not direct outplanting, during this time frame.

Fig. 17c-d. Object-based classification of coral features based on an orthophoto mosaic (2cm RGB) acquired with a DJI Phantom 4 Pro flying at 300ft on July 30, 2019 (L) and September 18, 2020 post-Nana. Here, the orange is replenished *A. cervicornis* and the red is natural/wild *A. palmata*.

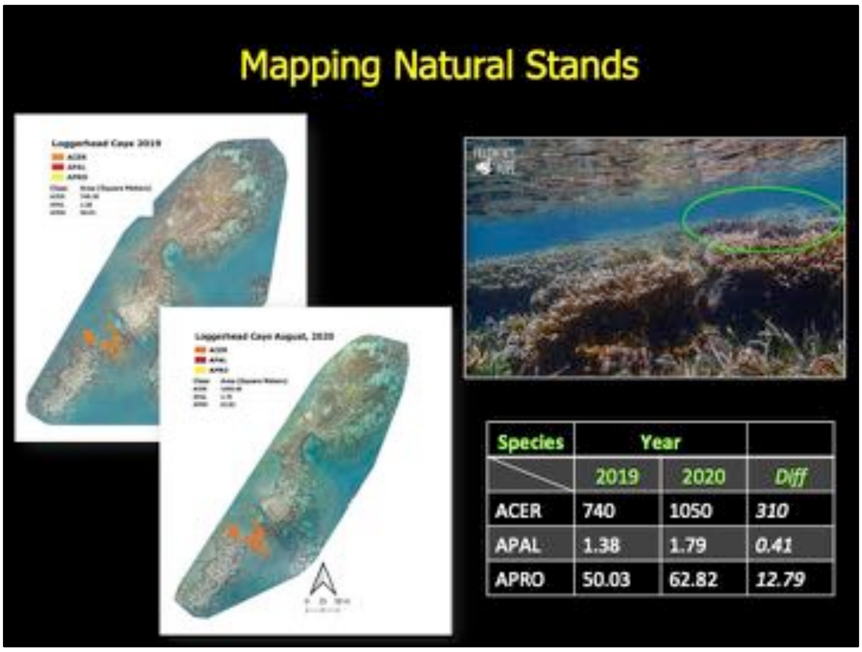


Fig. 18a. An example of one year change detection using ortho-mosaics made with drones, and quantified with Q-GIS, from a natural acroporid stand near Loggerhead Caye, near Placencia. The table in the figure shows changes in acroporid taxa coverage in m^2, pre-Hurricane Nana and pre-bleaching

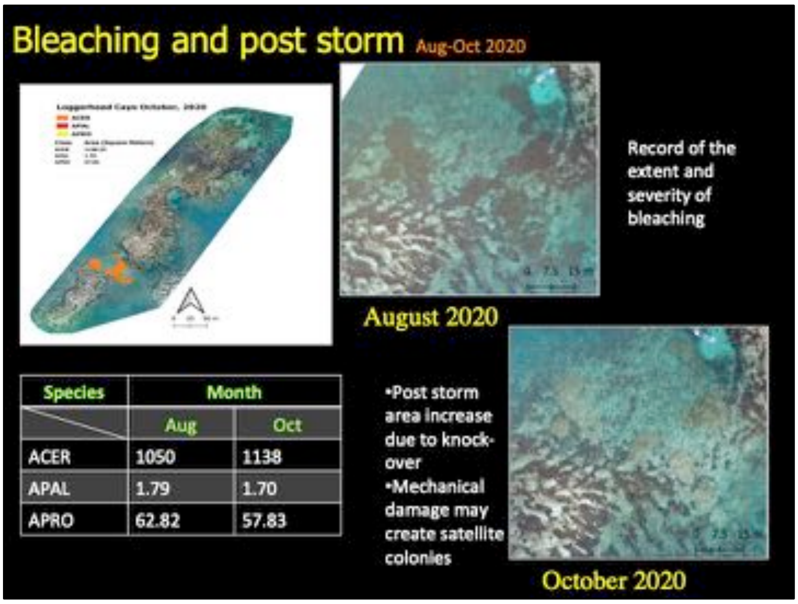


Fig. 18b. Example of using the drone ortho-mosaics to calculate changes after storms, and/or bleaching events. The change in acroporid cover was quantified shown in table as m^2, but the bleaching extent was not yet quantified at this site (not a regularly visited bleaching survey site).

Satellite imagery was purchased late 2020 for almost 171km^2 (Figure 19a) but annotation is just beginning: Dr. Steve Schill had to first manipulate the imagery and now the FoH team is working on creating several habitat (seagrass, mangroves, sand, reef, etc.) polygons in QGIS so that Dr. Schill can experiment with his AI software (eCognition) for annotation of the entire satellite imagery. The draft of those initial results is shown in Figure 19b; this work still requires ground-truthing.

Fig. 19a. Illustrating the area (171km2) of tasked (ordered, paid for) satellite imagery from November 2020.

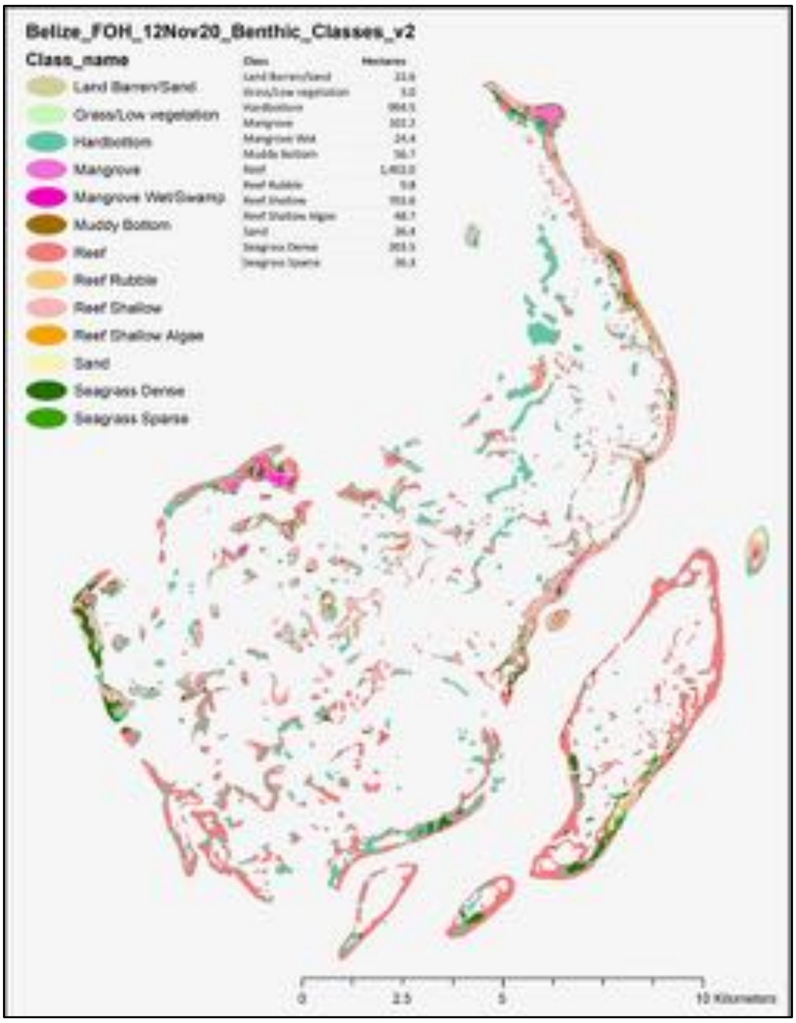


Fig. 19b. *Draft* benthic classification of purchased satellite imagery for 171km^2 of shallow water near Placencia. Note that in this draft, the reef categories (not including rubble) amount to 2,152 hectares; these classifications still require ground-truthing.

4) **Problems and Constraints.**

Besides the delays COVID caused for Dr. Gleason to complete the mosaics processing (due to restrictions/access to his computers at University of Miami), other issues still remain with the shallowest sites, often with the most growth, such as sub-site 13 at LBCNP (Figs. 15a and 17a). Ironically there is so much staghorn there now the software program cannot easily distinguish between individual photos, and thus we have no processed mosaics from this sub-site since 2018-19. Likewise with sub-site 23 2020 at LBCNP and and Moho 2 2019. The suggested solution was never to turn over large patches of staghorn (or plain sand), which results in collecting images over a far larger area than the original plot (~180m^2, Fig. 17a), which puts constraints on the cameras for both battery life and memory storage: usually two diver based mosaics can be conducted in a day, but now sub-site 13 must be done alone. This is also one of the reasons FoH is exploring the drone based mosaics, yet some caveats remain with this method as well. The caveats are the lower resolution on the drone ortho-mosaics, and the acroporids look very different in the drone mosaics than in reality (Figs. 18a), and in the diver-based mosaics. It is often difficult to distinguish the hybrid *A. prolifera* from the two other acropora species in the drone based ortho-mosaic: the solution to this is ground truthing. There is also subjectivity in quantifying the drone based ortho- mosaics just as there is in the diver based ortho-mosaics; some attempts were made using AI: but a person still has to 'tell' the software what is what, and initial attempts were not as accurate as quantifying the mosaics manually. The fish data FoH has been collecting over the years was initially analysed by Dr. Les Kaufman's PhD student, Karina Scavo, who was paid a small stipend under the IDB monies (2014-2016); although she continued for a few years (through 2019 for some sites), she no longer has time while finishing her thesis. FoH turned to Dr. John Bruno at the University of North Carolina when he offered assistance, and one of his undergraduate students has been working with the FoH fish data. However because her 2019 numbers do not match the previous 2019 results, this data was not included until the discrepancy can be sorted out.

5) **Unexpected effects.** The recent BBC article has generated the most donations and interest of any publications to date, including videos.

6) **Learning and Sharing.**

In addition to events listed under "Project Successes", two talks on FoH's work were given in November 2020 via Zoom to local students at Independence Junior College (IJC) and the University of Belize (UB). Also in November 2020 FoH sent two team members to assist UB's Dr. Leandra Cho-Ricketts' class with informal training on micro-fragmenting for their diadema translocation experiments at Calabash Caye, where they outplanted *Orbicella faveloata* micro frags onto the artificial "housing/domes" for diademas (Fig. 20a). L. Carne also assisted local UB student Ms. Brittney Garbutt with her undergraduate thesis on mapping acroporids in San Pedro-Ms. Garbutt had visited FoH on an outplanting field day in 2019. Carne was also a MSc thesis advisor to Dan Mele at the University of the Virgin Islands, who framed his thesis work based on FoH's direct outplanting of micro frags. He successfully defended/completed his thesis entitled "A comparison of micro-fragmenting propagation techniques for the endangered stony coral species, *Acropora palmata*" in April 2021 with 128 attendees via Zoom. Also in April 2021, FoH hosted a visitor to LBCNP from Antigua and Barbuda (Fig. 20b), who is interested in starting up restoration work there. Carne contributed photos, text, and edited the Coral Restoration Coalition's "Guide to Coral Reef Restoration: Methods to Optimize Efficiency and Scale". FoH contributes regularly to local, regional and international surveys and consultations;

one such example is a recent publication on coral transplantation[12]. FoH is in discussion with practitioners from the Punta Cana Foundation in the Dominican Republic, to host them for FoH training in Belize in early 2022 (originally planned prior to COVID and delayed). FoH also signed an MOE with SECORE[13] to join their team of implementation partners; specifically, this means trialing their “coral rearing in situ basins” (CRIBS) at LBCNP during the 2022 spawning season. FoH is also engaged with TASA on discussion of training for Turneffe’s private sector & TASA staff for expansion of the restoration work begun under the MCCAP project. Dr. Les Kaufman is using FoH diver mosaics for his restoration class(es) at Boston University, and FoH has engaged Dr. John Bruno, his undergraduate student, and his former PhD student, Dr. Colleen Bove, now a Postdoctoral Associate Lecturer at Boston University, for assistance with analyzing FoH fish and temperature data (Figs. 13b, 13d-e).

Figs. 20a-b. UB student measuring star coral fragments outplanted onto diadema “domes” at Calabash Caye (L) and visitor from Antigua/Barbuda at LBCNP (R).

7) **Adaptive Management.**

SCTLD continues to spread in Belize, with the latest reports showing it near Belize City and Goff’s Caye[14], and anecdotally (not yet confirmed) reported at the west side of Long Caye in Lighthouse Atoll (previous reports were only in the northern part of the atoll) and the south side of Tobacco Caye channel. Because of this FoH has aborted their previous plans to step up work with non-acroporid species, concentrating instead on increasing the genetic diversity of the three acropora taxa at each of the nurseries/outplant sites. FoH has also applied for additional funding to continue both training and acroporid replenishment work in the Northern MPAs in the short term, switching focus from the well-established southern sites.

[12] https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0249966

[13] http://www.secore.org/site/home.html

[14] https://www.agrra.org/coral-disease-outbreak/#sctld-dashboard

8) **Communications/ Stories.**

In addition to those highlighted under "Project Successes", FoH hosted an in-person AGM in August 2020 when participant numbers were allowed at 25, and their first ever virtual end of the year event via Zoom with almost 50 participants[15]. The "Earth Museum" hosts FoH work under their themed tours[16] and FoH is showcased on the UN's Decade of Restoration website[17]. L. Carne is a co-author on an accepted publication in Coral Reefs entitled "Two offshore coral species show greater acclimatization capacity to environmental variation than nearshore counterparts in southern Belize" with Dr. Justin Baumann et al.[18] (shared as Annex I). FoH was also approached to use photos for a publication by geneticist colleagues in Molecular Ecology entitled, "Genomic variation of an endosymbiotic dinoflagellate (*Symbiodinium 'fitti'*) among closely related coral hosts,"[19] with images from LBCNP shared in the Penn State News[20]. This and the BBC article has been shared by multiple media houses (Fig. 21), and translated to other languages (French), increasing FoH's Facebook followers to over 5,200, Instagram followers to 1,500, and Twitter followers to over 500. Likewise multiple German TV shows and articles have highlighted and reshared FoH work in several online formats in Europe. For the future, FoH is in dialogue with the European Nature Trust for a documentary on Belize scheduled to begin filming in 2022[21]. Also for 2022, FoH is engaged with the producers for "UnBelizeablue", a film planned to highlight women in conservation in Belize.

[15] https://drive.google.com/file/d/1SGwNFmLF9NTk_XsWs57pnvBd31lzsRGi/view?usp=sharing

[16] https://the-earth-museum.maps.arcgis.com/apps/webappviewer3d/index.html?id=74436df04b364fde98f33e0c93c801f0

[17] https://implementers.decadeonrestoration.org/implementers/20/fragments-of-hope

[18] https://link.springer.com/article/10.1007/s00338-021-02124-8

[19] https://onlinelibrary.wiley.com/doi/epdf/10.1111/mec.15952

[20] https://news.psu.edu/story/660120/2021/05/27/research/reef-building-corals-and-microscopic-algae-within-their-cells

[21] https://europeannaturetrust.s3.eu-west-2.amazonaws.com/2021/01/Belize-Uncovered-v1.0.pdf

9) **Challenges.** In addition to what is listed in Section 5 **Problems and Constraints,** inclement weather continues to be a challenge for outplanting and mapping days when certain conditions are required. January-May FoH only averaged four-five field days each month, due to weather constraints. FoH also closed most other grants in 2020, and the only active current grant for field work is from Mar Fund (begun August 2020). There was a three month wait between submitting the first technical report in mid-February, and receiving the 2nd disbursement, which also hindered the field work and several of the decent weather days for fieldwork were missed because of the long lag time in funding.

10) **Overall Assessment of Progress.** The work conducted by FoH has been ongoing since 2006 and supported by WWF since 2009. Barring a few missing diver-based mosaics data sets due to technical issues described above, the overall objectives for this contract were met and often exceeded, with the exception of the fish data. The fish data has been collected regularly; the issues are more than one data collector 2014-2020, sporadic external assistance in analyzing the data, and since 2019, FoH has been requesting Dr. Les Kaufman to revisit the protocols he created for FoH in 2014. FoH recognizes the need for this data analysis and will continue to source funds and persons to address all the raw data 2015-2021. Related, the ARMS[22] units deployed in replenished and unreplenished sites at LBCNP and Moho in January 2017 to assess the biodiversity of cryptofauna have still not been retrieved. This was deferred even prior to COVID, as the Smithsonian had switched focus to SCTLD. There is much work to complete to fill in gaps in assessing the related biodiversity changes that results from replenishing acroporids.

Report completed by:	
Name	**Lisa Carne**
Position/ Title	**Executive Director/Founder**
Organisation	**Fragments of Hope**
Date	**15 June 2021**

[22] https://naturalhistory.si.edu/research/global-arms-program