

Baseline Levels of *Siderastrea siderea* Bleaching under Normal Environmental Conditions in Little Cayman

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Abstract

This study describes the health status of *Siderastrea siderea* in Little Cayman before, during, and after the 2015 Caribbean-wide elevated temperature anomaly. Colony color was used as a proxy for health during snorkel and scuba surveys of shallow (<2 m depth) and deep (6 - 16 m depth) reefs. Baseline demographics indicated that 6% of this species were pale or blue pre-disturbance. When seawater temperatures exceeded 30.5°C, *S. siderea* were early indicators of reef stress and among the first corals to bleach. Depth and site resilience did not significantly impact temperature susceptibility; however, smaller colonies (<200 cm² surface area) were more likely to change color than the larger size classes. Little Cayman's *S. siderea* were capable of surviving large-scale (>80%) bleaching: mortality was observed for only one colony. Resilience rates varied considerably: one-third of the impacted population returned to the normal brown color within two months, one-third required 3 - 9 months to recover, and the fates of the remaining one-third remain to be determined. If the return to normal color is indicative of resistance to reef disturbances, *S. siderea* may be among the "winning" coral species following elevated temperature anomalies which are predicted to occur with increasing frequency and severity as a result of climate change.

Keywords

Siderastrea siderea, Bleaching Events, Demographic Study, Little Cayman, Caribbean

1. Introduction

Coral bleaching occurs when the long term average sea surface temperature (SST) is exceeded by 1°C or more during the warmest season [1]. With even a minimal rise in SST of 0.1°C, the geographic extent and intensity of coral bleaching may be increased

by 35% and 42%, respectively [2]. As tropical ocean temperatures are rising by 0.07°C - 0.5°C per decade, corals already near their thermal threshold are exposed to increasingly greater risk for bleaching [3]. In 2015, alerts warning of potential global-scale coral bleaching due to prolonged elevated seawater temperatures were broadcast among the scientific community. Bleaching threats continued through 2016. For example, Australia's Great Barrier Reef experienced extensive coral mortality, in what is considered one of the worst-case mass bleaching events on record, resulting from prolonged exposure to SSTs that were 1.0°C - 1.5°C higher than the long term summertime average [4].

In the Caribbean, Little Cayman is an ideal location to study best-case scenario responses of corals to elevated temperatures: it is a remote, low elevation, flat island (10 square miles) with a small population (<200 people) and without agriculture, runoff from rivers or streams, industry, and ports; providing the rare opportunity to decouple anthropogenic and environmental effects on the health of coral reefs. A Coral Reef Early Warning System (CREWS) buoy is moored above the reef on the north side of the island and records SST data along with other environmental parameters inside the eastern boundary of the Bloody Bay Marine Protected Area. Like many reefs around the world, Little Cayman's corals experienced bleached when exposed to above average SSTs in 2015.

Siderastrea siderea, commonly known as the massive starlet coral, is an abundant reef building coral in both shallow and deep Caribbean waters and is resilient when exposed to several non-ideal conditions [5]. Although *S. siderea* has been shown to have a stable relationship with its symbionts [6], it is one of the first species to bleach, making it a useful early indicator of disturbance events [7]. *S. siderea* has been observed to turn blue and other fluorescent colors as a stress response. *S. siderea* frequently survives bleaching events [8] [9] although colonies may remain blue for extended periods after the environmental stress conditions have dissipated.

This study describes the health status of *S. siderea* before, during, and after the 2015 Caribbean-wide elevated temperature anomaly as well as during 2016 "normal" (non-disturbance) temperatures. These data may subsequently be used to compare the health of *S. siderea* during normal conditions, bleaching events, and post-stress recovery periods. Knowing how certain coral species react to and recover from bleaching events is helpful in monitoring the resilience of coral reef ecosystems.

2. Methods

2.1. 2015 Rapid Assessment

Baseline surveys were conducted at five Little Cayman dive sites (6 - 16 m depth) within Bloody Bay Marine Park (Figure 1, Table 1) in June, 2015 before water temperatures reached the summer maximum. At each location, the color of *S. siderea* colonies was recorded along four 25-m line transects. Coral color was coded as: 1 = white, bleached; 2 = blue or other fluorescent color, bleached; 3 = partially bleached; 4 = brown/tan, unbleached. Site data were pooled to determine the pre-disturbance population of stressed (Codes 1 - 3) and healthy (Code 4) colonies.

Coral color was recorded at seven dive sites (6 - 16 m depth) within and eastward of

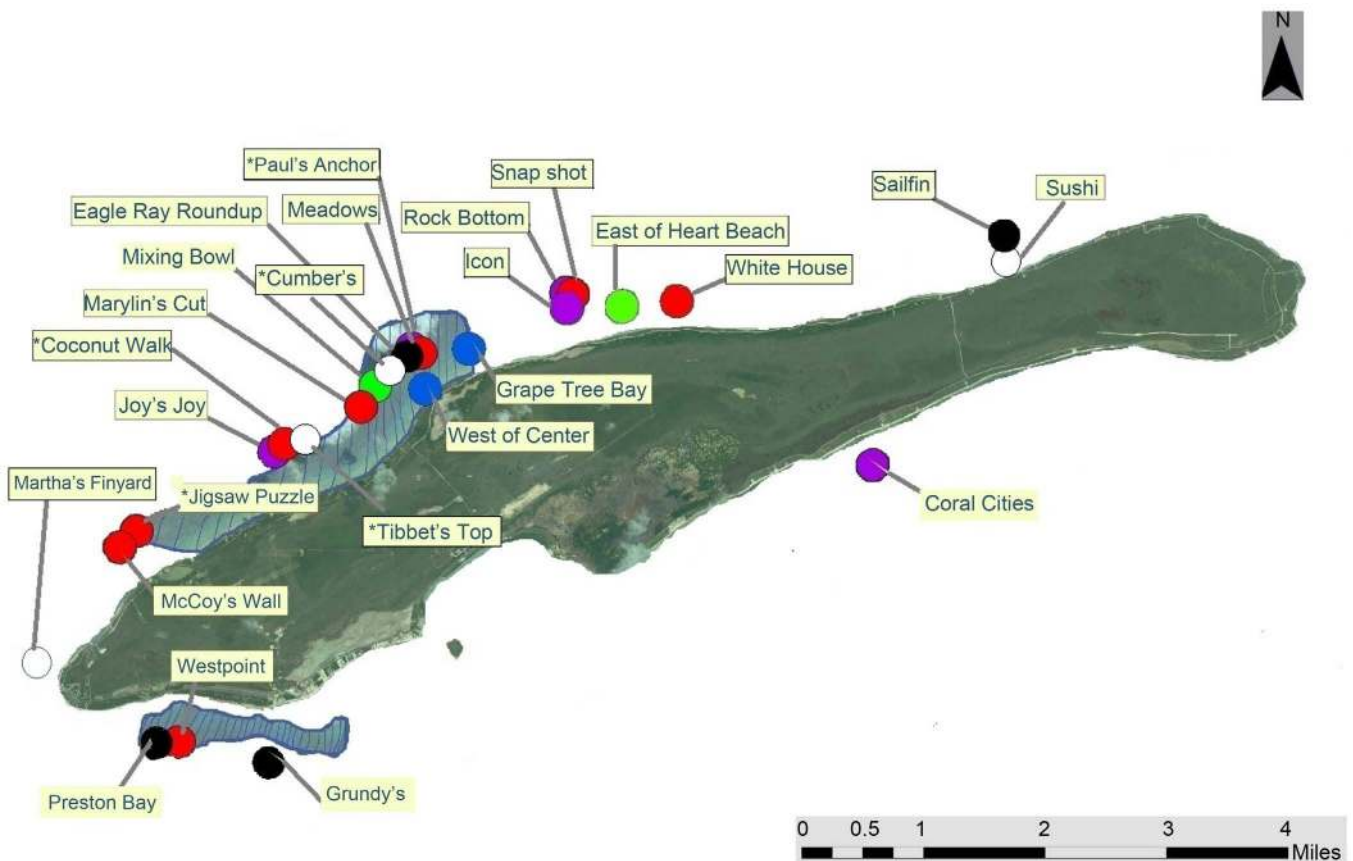


Figure 1. Map of *Siderastrea siderea* survey sites around Little Cayman. Colors represent Bray-Curtis similarity groupings during 2016 “normal” environmental conditions. Marine Protected areas are marked in striped blue. No spatial pattern is discernible based on these assemblages. White sites were not surveyed in 2016 and therefore were not included in the Bray-Curtis similarity test. The five baseline sites surveyed in June 2015, before water temperatures reached summer maximum are marked with asterisks.

Bloody Bay Marine Park in September and October, 2015 during the peak water temperatures to determine the population health during the bleaching event.

Coral color was recorded at three dive sites (6 - 16 m depth) and two shallow snorkel sites (<2 m depth) in November and December, 2015 when water temperatures were at or below the baseline survey temperatures to determine the population health during the first two months of post-bleaching recovery.

2.2. 2016 Demographic Surveys

Siderastrea siderea colony color was recorded at 21 sites around Little Cayman (Figure 1, Table 1) in June-July 5, 2016, before water temperatures reached the summer maximum, using a roving diver technique [10] whereby a minimum of 32 colonies per site were photographed with a digital underwater camera positioned directly above each colony to record its planar view. A meter stick with marks every 10 centimeters was placed next to the colony to use for scale during subsequent image analysis and size class determination.

Coral Point Count (CPCe) [11] was used to calculate the surface area of each *S. siderea* colony within the digital images (Figure 2). Colonies were grouped into six size classes based on the surface area of live tissue (Table 2).

Table 1. Survey sites around Little Cayman. Baseline survey sites from June 2015 are marked by asterisks.

Survey Site	Depth (Deep/Shallow)	Relative Resilience Level	Inside/Outside MPA	June 2015 Surveys	Sept-Oct 2015 Surveys	Nov-Dec 2015 Surveys	Jun-Jul 2016 Surveys
Coconut Walk*	Deep	Med-high	Outside	X	X		X
Coral City	Deep	Low	Outside			X	X
Cumber's*	Deep	Med-high		X			
Eagle Ray Roundup	Deep	Med-high	Inside				X
Eastof Heart Beach	Shallow	Med-low	Outside				X
Grape Tree Bay	Shallow	Med-high	Inside			X	X
Grundy's Garden	Deep	Med-high	Outside			X	X
Icon	Deep	Med-high	Outside		X		X
Jigsaw Puzzle*	Deep	Med-high	Outside	X			X
Joy's Joy	Deep	Med-high	Outside				X
Martha's Finyard	Deep	High	Outside		X		
Marylin's Cut	Deep	Med-high	Inside				X
McCoy's Wall	Shallow	Med-high	Outside				X
Meadows	Deep	Med-high	Inside				X
Mixing Bowl	Deep	Med-high	Inside		X		X
Paul's Anchors*	Deep	Med-high	Inside	X	X		X
Preston Bay	Shallow	Low	Inside				X
Rock Bottom	Deep	Med-low	Outside		X		X
Sailfin	Deep	Med-low	Outside				X
Snapshot	Deep	Med-low	Outside		X		X
Sushi	Shallow	Med-Low	Outside			X	
Tibbet's Top*	Deep	Med-high	Outside	X			
West of Center	Shallow	Med-high	Inside				X
Westpoint	Deep	Low	Inside			X	X
White House	Shallow	Med-low	Outside				X

Table 2. Size class groupings based on surface area of live tissue (2016).

Size Class	Surface Area (cm ²)	% of Surveyed Population
SC1	<200	39%
SC2	200 - 400	17%
SC3	400 - 600	12%
SC4	600 - 800	7%
SC5	800 - 1000	5%
SC6	>1000	20%

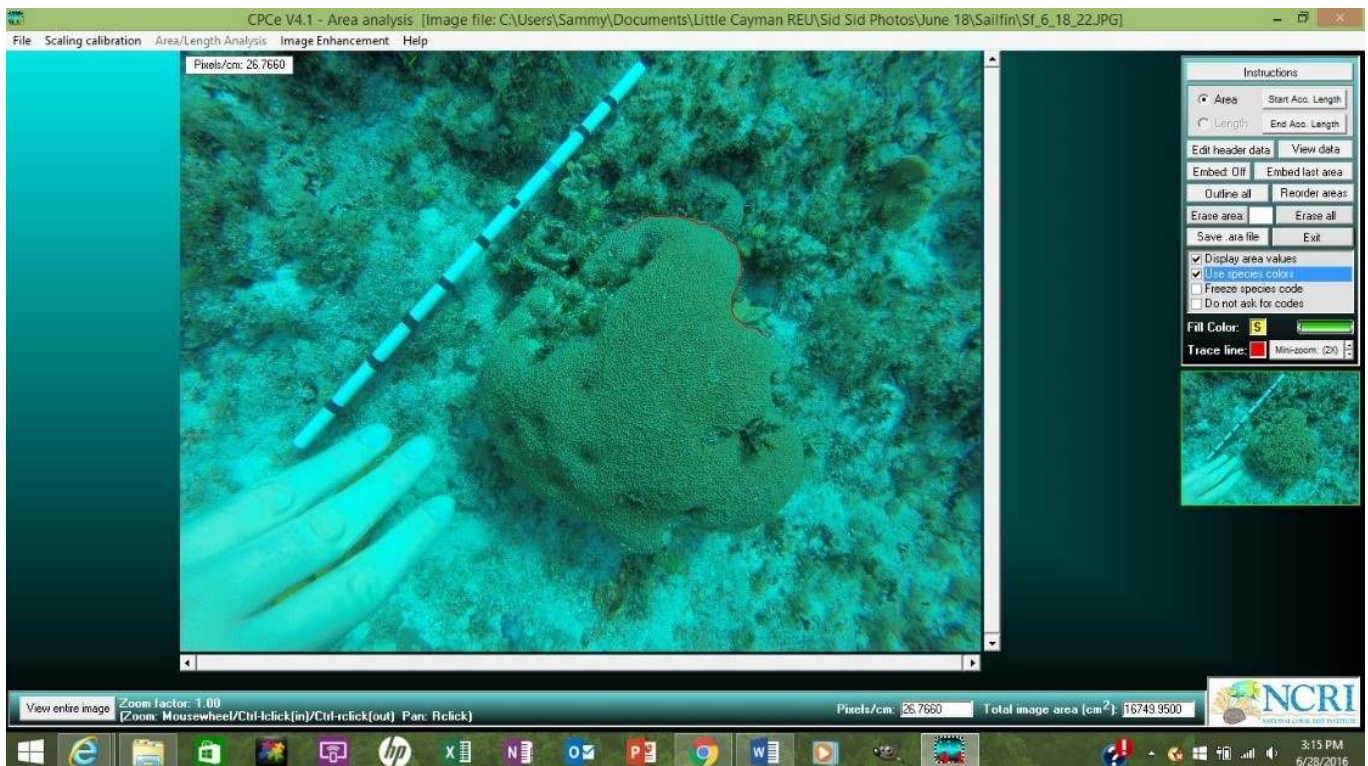


Figure 2. Image analysis of *S. siderea* colony to determine surface area using CPCe. The meter stick provides scale for the colony surface area and size class determination. The number of fingers in the image represents the coded health status of the colony.

Spatial comparisons of the unhealthy *S. siderea* colonies around Little Cayman were conducted using Primer software [12]. Data were organized by size class and survey site. A fourth root transformation was performed to minimize the effect of any large differences between zero and non-zero values during analysis. A triangular similarity matrix was created and used to calculate the Bray-Curtis Similarity index between sites [13]. A hierarchical agglomerative cluster analysis [13] was used to create assemblages with $\geq 70\%$ within-group similarity.

Non-parametric, one-way, pair-wise analysis of similarity (ANOSIM) tests determined whether sites were statistically significantly different [13] based on depth and on site resilience. Site resilience was determined during a previous study (unpublished data) based on six indicators of coral reef resilience: coral diversity, macroalgae cover, coral cover, bleaching resistance, coral recruitment, temperature variability, and herbivore biomass. Similarity of percentages (SIMPER) tests determined which size classes contributed most to similarities within and dissimilarities between site groupings [13].

Wilcoxon-Mann-Whitney tests were performed to compare the health status of *S. siderea* before, during, and after exposure to the elevated seawater temperatures and between size classes.

2.3. Sea Surface Temperatures

Twice daily SSTs recorded by the Little Cayman CREWS buoy in the 06:00 and 18:00 hours are archived in NOAA's open access Coral Health and Monitoring Program (CHAMP) Portal database [14]. The 18:00 hour data from July-October in 2014, 2015,

and 2016 were plotted to provide annual comparisons of the SSTs during the months when coral bleaching alerts for the Caribbean were issued by NOAA (Figure 3).

3. Results

In June 2015, when maximum water temperatures surrounding Little Cayman's reefs were 29°C, 6% of the *S. siderea* colonies were pale or blue (Figure 4), thereby establishing the pre-disturbance baseline of stressed colonies within a "normal" population. No colonies were fully bleached (white) and no tissue loss or recent mortality was observed.

Between August and October, water temperatures around the reef (6 - 16 m depth) frequently exceeded the local typical summertime maximum of 30.5°C (Figure 3) [14], causing wide-scale paling and bleaching. 82% of the observed *S. siderea* colonies, or an additional 76% beyond the baseline, displayed signs of stress (Figure 4): 23% were pale,

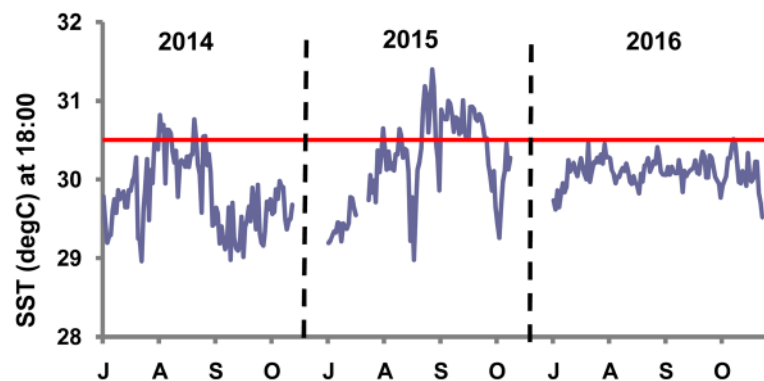


Figure 3. Temporal comparison of SST in Little Cayman during 2014-2016 bleaching alert periods. Data courtesy of NOAA's open access CHAMP Portal database. Red line indicates normal summertime maximum temperature in Little Cayman (30.5°C) below which widespread bleaching does not occur.

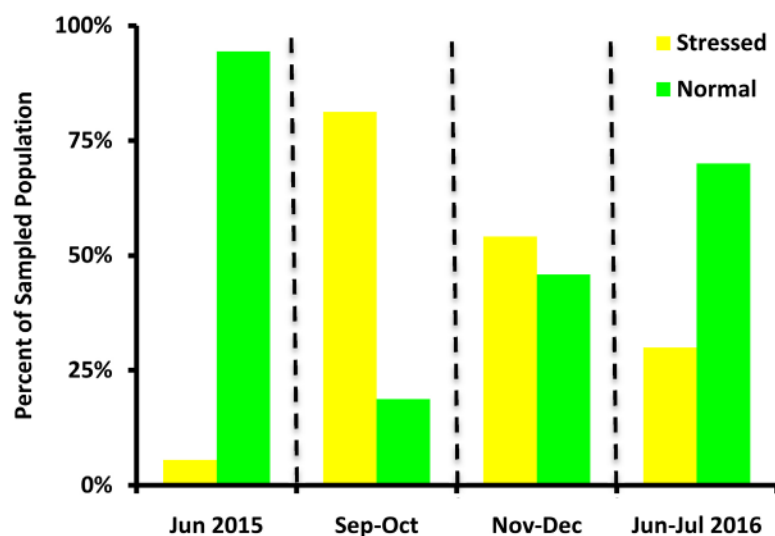


Figure 4. *Siderastrea siderea* health status in Little Cayman between June 2015 and July 2016. All time frames are statistically significantly different (Wilcoxon-Mann-Whitney analysis).

59% were blue, and a single colony had bleached white. Wilcoxon-Mann-Whitney analyses confirmed the sample population health during this period of stress was statistically significantly different compared to the June 2015 baseline ($\alpha = 0.05$; $P = 0.006$). Adverse weather during the first week of October resulted in several days of cloud cover and heavy wind, waves, and rain which brought relief to the reef through reduced water temperatures before significant bleaching or mortality occurred.

By November and December, water temperatures within the shallow lagoon and deeper reefs dropped to 28°C - 29°C and 27°C - 28°C, respectively, below the temperatures during the June assessments. 54% of the *S. siderea* colonies displayed signs of stress (**Figure 4**): 25% were pale, 29% were blue, and no colonies were fully bleached (white) indicating rapid short-term recovery of ~28% of the population within two months of the elevated temperature disturbance. Wilcoxon-Mann-Whitney analyses ($\alpha = 0.05$) confirmed the statistically significant recovery compared to the September-October sample ($P = 0.033$), but the population was still stressed compared to June ($P = 0.010$). The largest recovery occurred within the blue colonies, with approximately half of those returning to normal color (*i.e.* 59% of the surveyed corals were blue in Sept-Oct compared to 29% in Nov-Dec).

The *S. siderea* population continued to recover during the first half of 2016 but 30% of the sampled population remained stressed, five times higher than the June 2015 pre-disturbance baseline (**Figure 4**). Wilcoxon-Mann-Whitney analyses ($\alpha = 0.05$) confirmed the statistically significant recovery compared to November-December ($P = 0.012$), but the population had not returned to “normal” ($P = 0.006$). The health status of the surveyed population suggests that more than a year is required for the *S. siderea* population to recover from exposure to elevated temperatures.

Size class frequency distributions indicated that the smallest corals (<200 cm² surface area) comprised the largest group within the surveyed population (**Table 2**) and approximately half of the stressed colonies in the June-July 2016 surveys (**Figure 5**). Wilcoxon-Mann-Whitney analyses ($\alpha = 0.05$) indicated the health status of Size Classes 2 and 6 were statistically significantly similar ($P = 0.934$) as were Size Classes 3 and 4 ($P = 0.167$) and Size Classes 4 and 5 ($P = 0.075$). All other size classes were statistically significantly different from each other.

Hierarchical agglomerative cluster analysis revealed that all sites sampled in 2016 shared at least a 40% similarity based on the percent of stressed colonies in each size class (**Figure 6**). Four subsets of the population had a 70% similarity among the sites comprising each respective assemblage (**Figure 6**). However, when these sites were plotted on the map of Little Cayman (**Figure 1**), no spatial patterns were discernible based on the assemblages generated by the Bray-Curtis analysis, suggesting that depth and relative site resilience do not influence the prevalence of pale and blue colonies within the population. ANOSIM results confirmed that *S. siderea* health was not statistically different between shallow (<2 m depth) and deep (>6 m depth) sites (R statistic = 0.36) or between sites with various resilience rankings (R statistics = 0.13).

SIMPER analyses identified the *S. siderea* size classes which contributed to the within-group similarities and among-group dissimilarities. Corals with surface areas below 200 cm² (Size Classes 1 and 2) and above 1000 cm² (Size Class 6) contributed most to

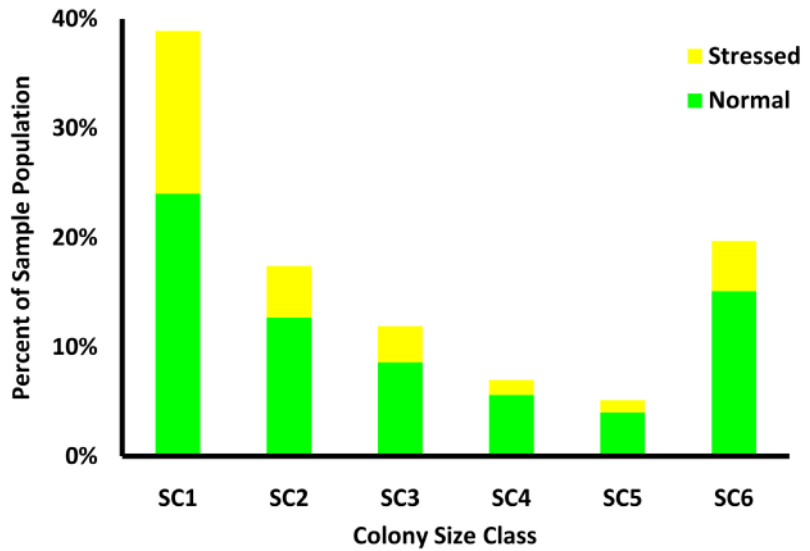


Figure 5. Health status of *S. siderea* in Little Cayman by colony size class distribution in June-July 2016. The health status is statistically similar between size classes (i) SC2 and SC6; (ii) SC3 and SC4 and (iii) SC4 and SC5. All other size classes are statistically significantly different from each other (Wilcoxon-Mann-Whitney analysis).

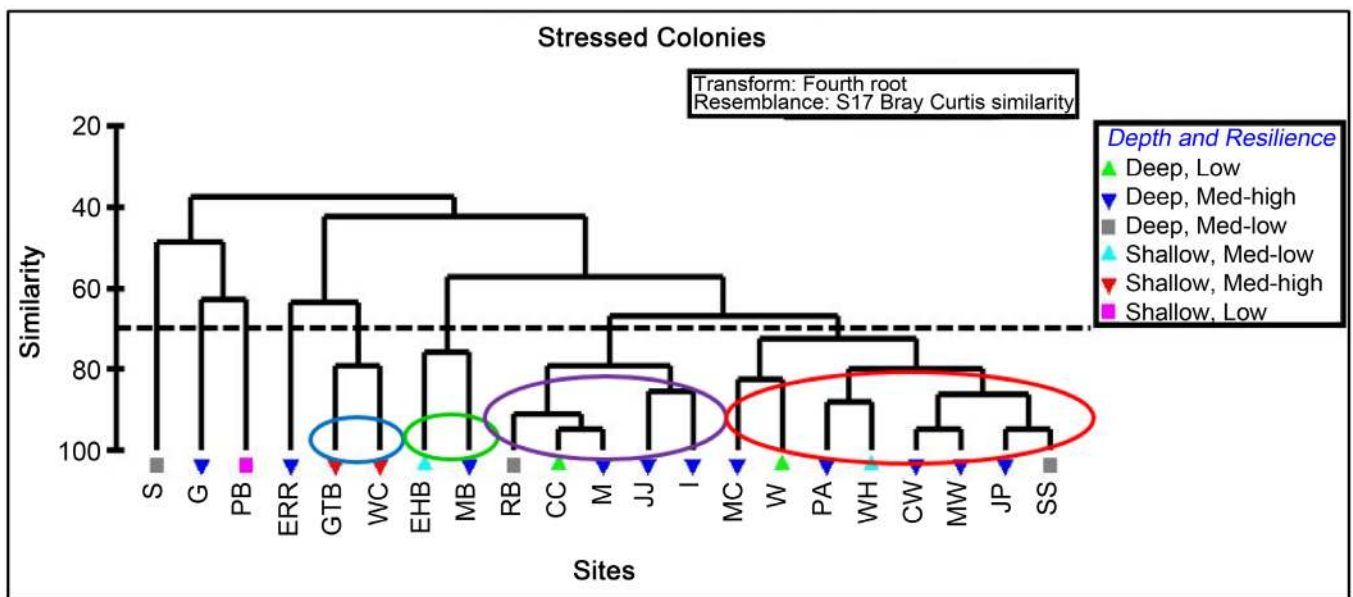


Figure 6. Bray-Curtis similarity cluster analysis depicting four assemblages. Colored ovals represent groups of sites with >70% similarity based on health status within six colony size classes.

the (dis)similarities between shallow and deep sites (Table 3). Corals with surfaces areas between 600 - 1000 cm² (Size Classes 4 and 5) contributed least to the (dis)similarities between the low, medium-high, and medium-low resilience sites (Table 4).

T-test results show.

4. Discussion

Temperature-induced bleaching occurs when the long term average sea surface temperature

Table 3. Within-group similarities and among-group dissimilarities from SIMPER analysis of depth. Cont. (%) is the percentage (dis)similarity contributed by the respective size class. Cum. (%) is the cumulative percentage of (dis)similarity.

Group A: Deep Sites			Groups: Deep vs Shallow		
Average similarity: 62.17	Cont. (%)	Cum. (%)	Average dissimilarity: 53.10	Cont. (%)	Cum. (%)
SC1	37.04	37.04	SC1	22.22	22.22
SC2	29.03	66.08	SC6	20.28	42.51
SC3	16.10	82.18	SC2	20.18	62.68
SC6	10.14	92.32	SC3	15.53	78.21
			SC4	11.70	89.92
			SC5	10.08	100.00
Group B: Shallow Sites					
Average similarity: 34.04					
SC6	33.44	33.44			
SC1	27.75	61.19			
SC3	26.86	88.05			
SC2	5.99	94.04			

(SST) is exceeded by 1 °C or more during the warmest season, and can be detrimental to the health of the reef ecosystem [1]. However, even a 0.1 °C rise in sea surface temperature has been reported to increase the average number of coral colonies affected by bleaching by 42% [2]. In a bleaching event, a coral loses the zooxanthellae that give the colony its color, as well as energy, which may result in the whitening of part or all of a coral's tissue and often times death [15].

The zooxanthellae, however, are not the only source of energy for some species of coral. Endolithic algae have been shown to rise to the coral tissue surface in certain species when zooxanthellae have been expelled during bleaching events. Endolithic algae as well as organic particles from sediment can serve as alternative energy sources in the absence of zooxanthellae allowing some corals to survive bleaching events [16] [17]. The blue bleaching by *Siderastrea siderea* may be due to the presence of endolithic algae [16], which may contribute to the survival of *S. siderea* during disturbance events.

The study described herein shows that *S. siderea* colonies in Little Cayman are able to withstand and quickly recover from temperature anomalies similar to those experienced in 2015. While frequent exposure to SSTs above 30.5 °C caused 76% of the observed *S. siderea* colonies to pale or bleach blue, only a single colony was observed to bleach white. In the first two months following the return to "normal" seawater temperatures, approximately one third of the stressed *S. siderea* colonies had returned to their healthy brown color. Another one third of the stressed population returned to their healthy brown color 3 - 9 months after the disturbance subsided. SSTs in 2016 stayed below the typical summertime maximum, which will hopefully promote further recovery of the remaining one third of the stressed colonies to pre-disturbance health.

Table 4. Within-group similarities and among-group dissimilarities from SIMPER analysis of site resilience. Cont. (%) is the percentage (dis)similarity contributed by the respective size class. Cum. (%) is the cumulative percentage of (dis)similarity. Site resilience based on six indicators of coral reef resilience: coral diversity, macroalgae cover, coral cover, bleaching resistance, coral recruitment, temperature variability, and herbivore biomass (unpublished data).

Group A: Low Resilience			Groups: Low vs Med-High		
Average similarity:	Cont. (%)	Cum. (%)	Average dissimilarity:	Cont. (%)	Cum. (%)
48.73			53.50		
SC1	82.34	82.34	SC6	24.81	24.81
SC2	17.66	100.00	SC1	19.26	44.07
			SC3	18.26	62.33
			SC2	16.30	78.63
			SC5	10.91	89.53
			SC4	10.47	100.00
Group B: Medium-High Resilience			Groups: Low vs Med-Low		
Average similarity: 59.31			Average dissimilarity: 48.70		
SC2	26.29	26.29	SC3	22.92	22.92
SC1	24.22	50.50	SC2	19.25	42.16
SC6	21.75	72.25	SC6	16.96	59.12
SC3	19.42	91.67	SC1	16.29	75.41
			SC5	12.45	87.86
			SC4	12.14	100.00
Group C: Medium-Low Resilience			Groups: Med-High vs Med-Low		
Average similarity: 49.49			Average dissimilarity: 43.04		
SC1	45.39	45.39	SC6	21.24	21.24
SC3	21.76	67.15	SC1	19.73	40.97
SC2	17.94	85.09	SC2	17.05	58.01
SC6	7.58	92.68	SC3	16.36	74.37
			SC4	13.92	88.29
			SC5	11.71	100.00

Manfrino *et al.* [18] recorded similar *S. siderea* bleaching resistance during the 2005 and 2010 bleaching events in Little Cayman. The hardiness of *S. siderea* leads to survival following certain elevated temperature anomalies which may, in turn, lead to a future phase shift from other dominant reef building corals to *S. siderea* [19], as many of these other species are more susceptible to bleaching and mortality when exposed to non-

ideal conditions [20].

Other studies have shown that physical stress in a reef ecosystem is more common in shallower versus deeper depths [21]. In southern Belize, *S. siderea* colonies on the fore-reef experienced higher susceptibility to stressors than colonies on the shallower back-reef and nearshore [22]. In the Florida Keys, land use and water management were determined to affect the quality and amount of freshwater runoff flowing into the bay, thereby causing stress to the shallow, nearshore corals [23]. The lack of depth-dependent stress found in Little Cayman's *S. siderea* population may be due, in part, to the minimal land-based pressures associated with the remote island.

5. Conclusion

This study describes the baseline health status within the *Siderastrea siderea* population around Little Cayman before, during, and after the 2015 elevated temperature anomaly. These data may subsequently be used to compare the health of *S. siderea* during future bleaching events and post-stress recovery periods. This species is an early indicator of stress on the reef and may be used to alert researchers to an impending bleaching event. During "normal" non-disturbance conditions, approximately 6% of the Little Cayman *S. siderea* population may appear blue or pale which must be taken into account when assessing the net impacts of a disturbance to coral health. These corals are capable of surviving a five-week exposure to SSTs above the normal summertime maximum, making them one of the more resilient species. Post-disturbance recovery occurs within nine months for roughly two-thirds of the stressed corals. Recovery times for the remaining one-third of the affected corals have not yet been determined. Long-term impacts (e.g. reproduction rates, susceptibility to subsequent stressors) also require future study. If the return to normal color is an indicator for short- and long-term resilience, *S. siderea* may be among the "winning" coral species following elevated SST anomalies.

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