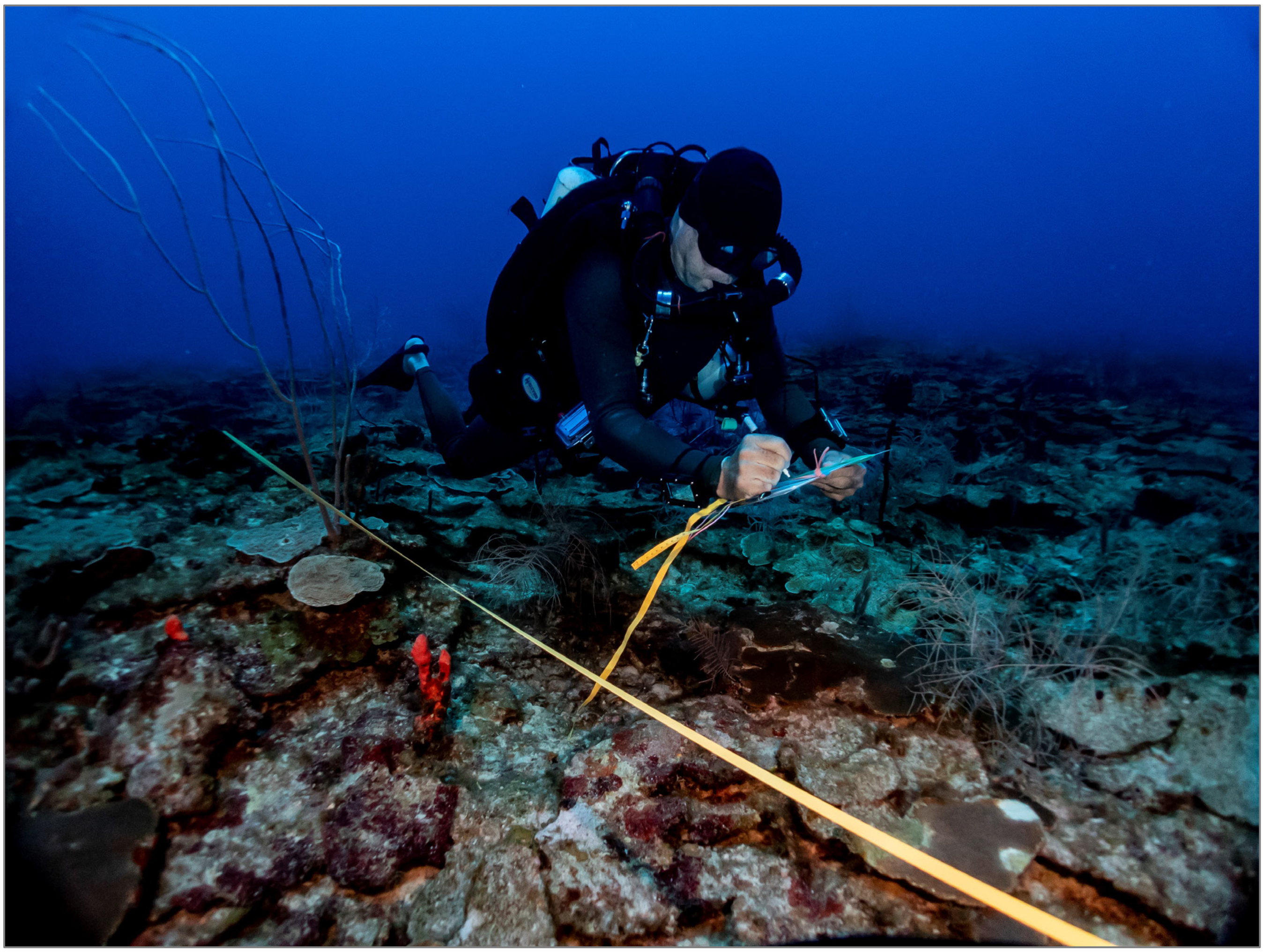
National Park Service
U.S. Department of the Interior

Science Report NPS/SR—2026/459
https://doi.org/10.36967/2318409

Coral Monitoring in Buck Island Reef National Monument

2025 Coral Monitoring Status Report



A diver conducts a benthic assessment along a transect in Buck Island Reef National Monument at the Buck Island Bar coral monitoring site.

NPS / LEE RICHTER

Coral Monitoring in Buck Island Reef National Monument: 2025 Coral Monitoring Status Report

Science Report NPS/SR—2026/459

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Please cite this publication as:

Richter, L., M.W. Feeley, and A. Kreyer. 2026. Coral Monitoring in Buck Island Reef National Monument: 2025 Coral Monitoring Status Report. Science Report NPS/SR—2026/459. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/2318409

NPS 163/199750, July 2026

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Abstract

Coral reef ecosystems are among the most ecologically significant resources managed by the National Park Service (NPS). Long-term monitoring provides the scientific foundation needed to evaluate reef condition and track ecological change. The South Florida/Caribbean Network (SFCN) conducts coral reef monitoring at Buck Island Reef National Monument (NM) to assess trends in benthic community composition.

This report synthesizes more than two decades of data from two monitoring sites: South Fore Reef (SFR), a shallow fore reef monitored since 2002, and Buck Island Bar (BAR), a deeper mesophotic reef monitored since 2017. Both sites are dominated by *Orbicella* spp., which are historically important reef-building corals in the Caribbean.

Coral community dynamics at both sites appear to be driven primarily by episodic disturbance events. At SFR, stony coral cover remained relatively stable until 2005, when a severe bleaching event and subsequent White Plague outbreak caused an approximately 80% decline. Coral cover partially recovered between 2007 and 2021. The emergence of Stony Coral Tissue Loss Disease (SCTLD) in 2021 resulted in rapid declines at both sites, with coral cover decreasing by approximately 70% at BAR and approximately 42% at SFR. Severe thermal stress in 2023 and 2024 led to additional declines in coral cover and species richness. In contrast, moderate bleaching events and major hurricanes produced limited and short-lived effects at the monitored sites.

Gorgonian cover remained relatively stable throughout the monitoring period, whereas stony coral communities exhibited shifts in composition, including declines in dominant reef-building corals and increasing relative abundance of more disturbance-tolerant taxa. The remaining assemblage is increasingly composed of taxa that are either relatively abundant, less susceptible to disease and thermal stress, or both.

These findings suggest that infrequent but severe disturbances are the primary drivers of long-term coral decline in Buck Island Reef NM, with site-specific responses influenced by depth, community composition, and host density.

Introduction

Understanding the condition of natural resources is essential for the National Park Service (NPS) to effectively protect and manage parks. Across the country, park managers face increasingly complex challenges and must rely on scientifically sound data to guide and justify their decisions. Long-term monitoring provides the scientific foundation needed to track ecological change and support informed management decisions.

The NPS has clear responsibilities for monitoring and managing natural resources under the Organic Act of 1916, with additional direction for coral reef conservation provided through Executive Order (EO) 13089 (1998) and the Coral Reef Action Plan (CRTF 2000). More recent federal priorities further emphasize the use of high-quality scientific information in resource management decision-making (EO 14276 [2025], EO 14303 [2025], Secretary's Order (SO) 3441 [2025], SO 3447 [2026]). Within this context, long-term coral reef monitoring provides critical data to support informed management decisions in Buck Island Reef National Monument and across the National Park System.

Buck Island Reef National Monument (NM) contains extensive coral reef ecosystems that are among the most ecologically important resources within the monument. Coral reefs support high biodiversity, contribute to fisheries and coastal protection, and serve as critical habitat for a wide range of marine organisms (NPS 2009; van den Hoek and Bayoumi 2017). Despite their importance, coral reef ecosystems are highly vulnerable to stressors including bleaching from marine heat waves, disease outbreaks, and hurricanes (Miller et al. 2017; Rogers 2022).

The ecological importance and splendor of the reefs in Buck Island Reef NM was described in 1969 by renowned marine scientist Jack Randall as "undoubtedly the most magnificent coral reef in the possession of the United States" (Randall 1969). His observations led to research in the 1960s and 1970s on the *Acropora palmata* (elkhorn coral) populations that initially dominated the shallow waters in the monument, but suffered catastrophic declines due to White Band Disease and Hurricanes David in 1979 and Hugo in 1989 (Gladfelter et al. 1977; Rogers 2022; Rogers et al. 2003). Research shifted to other coral species with routine monitoring efforts occurring at three sites in Buck Island Reef NM from 1988 to 2000 (Bythell et al. 1993, 2000). This project continued with annual monitoring and was the driver for the development of a USGS/NPS protocol on coral colony monitoring (Phillips 2002; Rogers and Catanzaro 2002). That led to the long-term coral monitoring conducted by the South Florida/Caribbean Network (SFCN) that continues to this day (Miller and Rogers 2002; Miller et al. 2017).

Coral reef communities are the highest priority "vital sign" monitored by the SFCN (Patterson et al. 2008). The NPS defines vital signs as a selected set of ecological attributes—physical, chemical, or biological—that serve as indicators of ecosystem condition or hold significant human value (Fancy et al. 2009). The SFCN coral reef monitoring program uses standardized methods to quantify changes in benthic community composition at selected long-term monitoring sites (Miller et al. 2017).

Monitoring is conducted at designated "index sites," which are selected for their ecological significance, management relevance, or historical importance (Miller et al. 2017). These sites are not randomly selected; therefore, results are intended to describe trends at the monitored reefs rather than represent all reef habitats within the park. Monitoring is designed to address how benthic communities change over time at these selected coral reefs.

Research Questions

This report synthesizes long-term monitoring data to evaluate temporal trends in benthic community composition at two monitoring sites: South Fore Reef and the Buck Island Bar (Figure 1). It examines how stony coral and gorgonian communities have changed over time and whether major disturbance events—such as marine heat waves, disease outbreaks, and hurricanes—correspond with observed shifts in benthic metrics. By comparing these factors across sites and years, the study identifies trends and assesses whether similar ecological responses are observed in different reef zones. The following research questions were developed to guide this report:

- How does stony coral cover change over time?
- How does gorgonian (soft coral) cover change over time?
- How does stony coral species richness change over time?
- How have disturbance events (coral disease, bleaching, hurricanes) affected reef composition?
- Are similar trends seen at the shallow (South Fore Reef) versus deep (Buck Island Bar) sites?

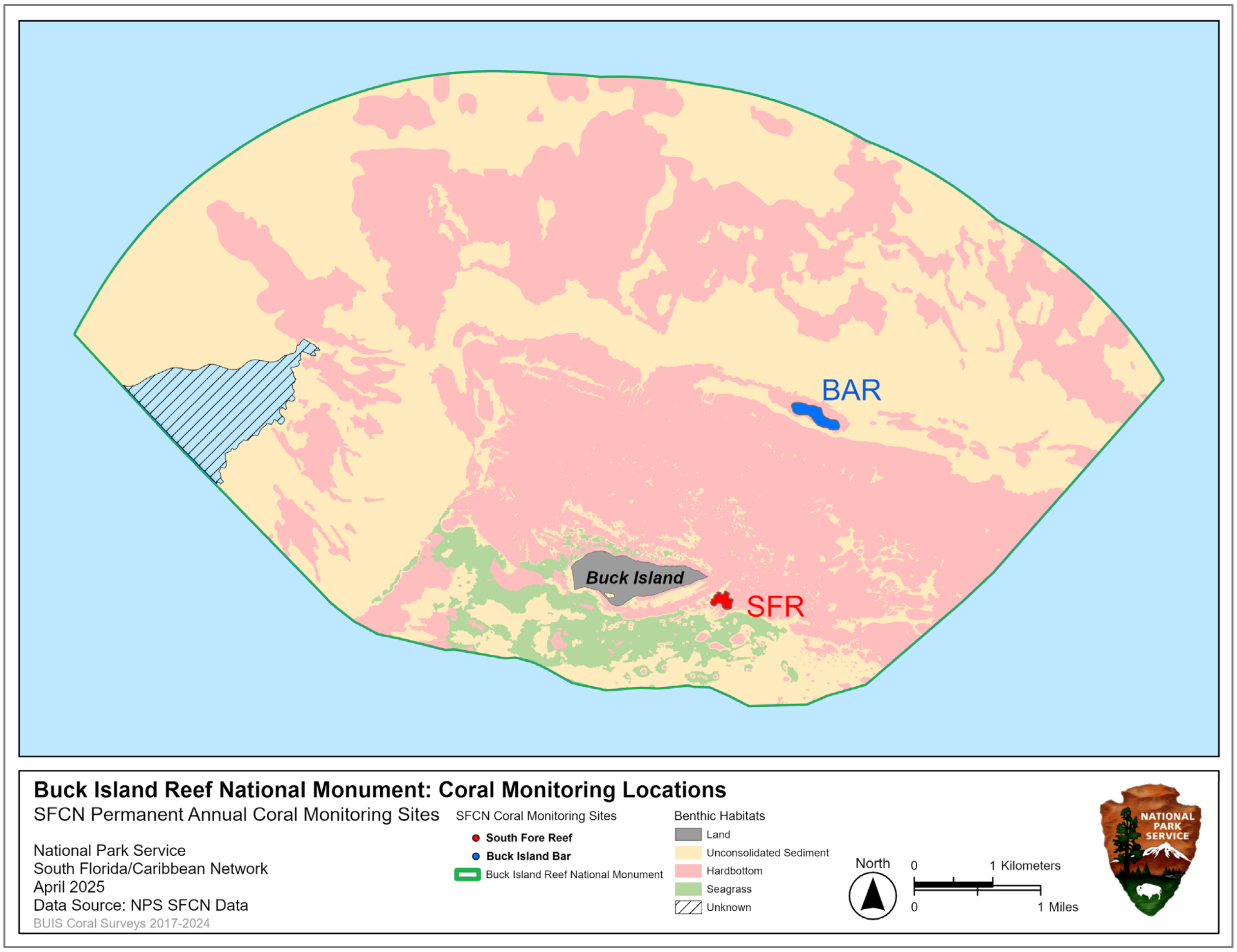

Figure 1. A map of the South Fore Reef (SFR) and Buck Island Bar (BAR) coral monitoring locations in Buck Island Reef National Monument.

NPS / SFCN

Methods

Monitoring Locations and History

In 1999, SFCN scientists collaborated with Buck Island Reef NM resource managers to conduct preliminary investigations to identify key reefs for long-term coral monitoring based on depth, size of reef area, composition, diversity and complexity of reef structures. In 2002, South Fore Reef was established as a prioritized coral monitoring location. In 2017, another monitoring location, the Buck Island Bar, was identified as a priority due to exceptionally high coral cover. All collected data from annual and episodic monitoring at both sites are used in these analyses.

South Fore Reef (SFR)

This site encompasses 40,753 square meters (9.9 acres [ac]) of fore reef habitat that typifies the southern waters of Buck Island Reef NM. It represents a highly complex, high coral cover reef dominated by mounding *Orbicella* spp. (Figure 2). Depths range from 11 to 15 meters (36–49 feet [ft]). Monitoring began in 2002 and continued annually, typically between February and April. Initially, only videography was conducted during annual monitoring from 2002 to 2005. As the monitoring program expanded, a disease assessment was later added in 2005, then a species assessment and colony count component in 2010. Episodic monitoring occurred in November 2005 in response to a severe bleaching event and disease outbreak. A second episodic monitoring event occurred at SFR in October 2010 in response to a moderate bleaching event (Table 1).

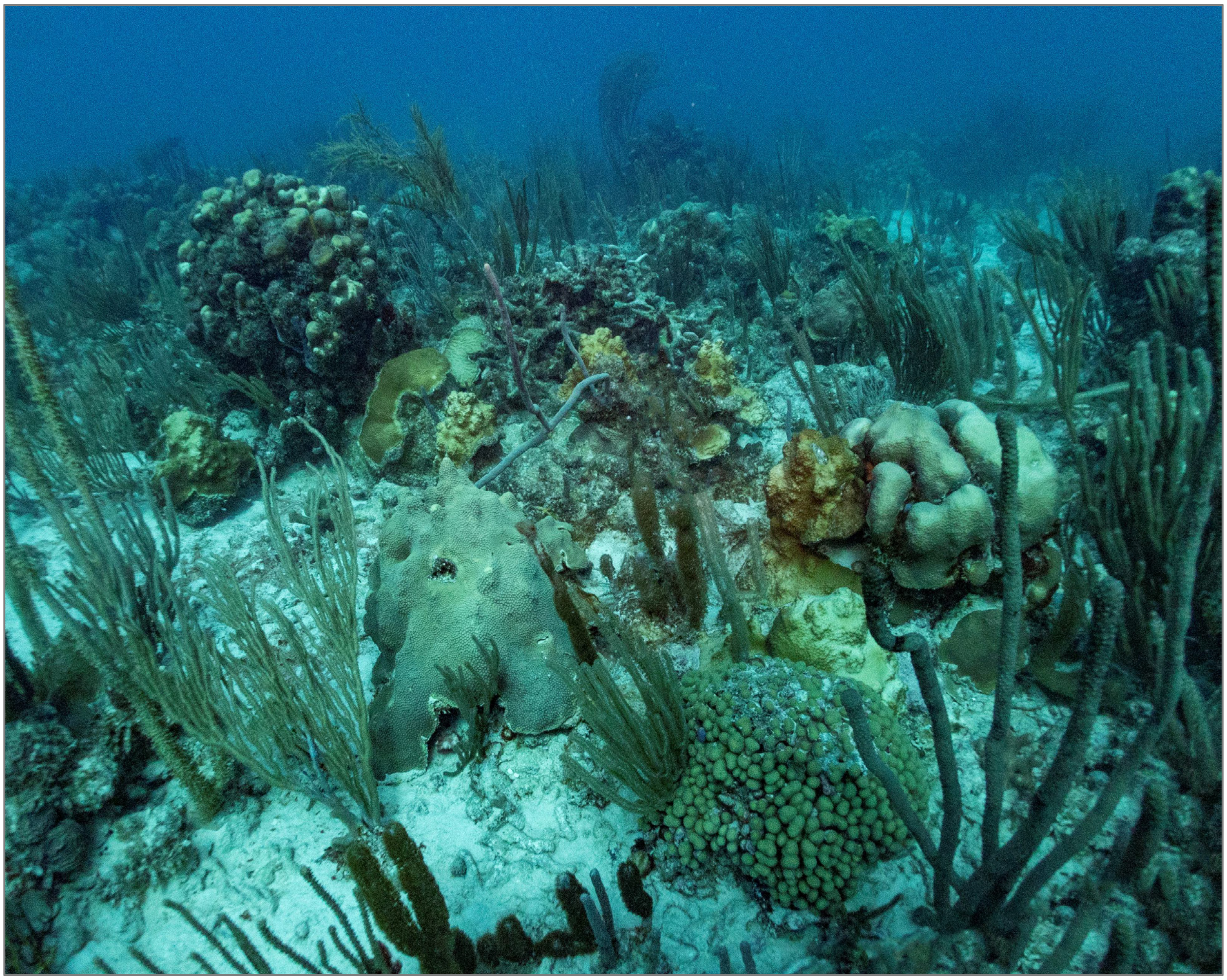

Figure 2. A typical view at the South Fore Reef monitoring site, where a dense network of corals is dominated by mounding *Orbicella* species.
NPS / LEE RICHTER

Table 1. Chronology of benthic monitoring events at South Fore Reef and the Buck Island Bar. Months represent when annual monitoring occurred.

Year	South Fore Reef			Buck Island Bar		
	Benthic cover (videography)	**Disease Assessment**	**Species Richness**	**Benthic cover (videography)**	**Disease Assessment**	**Species Richness**
2002	Feb	–	–	–	–	–
2003	Feb	–	–	–	–	–
2004	Mar	–	–	–	–	–
2005	Feb and *Nov* [A]	Feb and *Nov* [A]	–	–	–	–
2006	Mar	Mar	–	–	–	–
2007	Feb	Feb	–	–	–	–
2008	Feb	Feb	–	–	–	–
2009	Feb	Feb	–	–	–	–

Table 1 (continued). Chronology of benthic monitoring events at South Fore Reef and the Buck Island Bar. Months represent when annual monitoring occurred.

Year	South Fore Reef			Buck Island Bar		
	Benthic cover (videography)	**Disease Assessment**	**Species Richness**	**Benthic cover (videography)**	**Disease Assessment**	**Species Richness**
2010	Jan and *Oct*[A]	Jan and *Oct*[A]	Jan and *Oct*[A]	–	–	–
2011	Feb	Feb	Feb	–	–	–
2012	Feb	Feb	Feb	–	–	–
2013	Feb	Feb	Feb	–	–	–
2014	Feb	Feb	Feb	–	–	–
2015	Feb	Feb	Feb	–	–	–
2016	Feb	Feb	Feb	–	–	–
2017	Feb	Feb	Feb	Apr	Apr	Apr
2018	Feb	Feb	Feb	May	May	May
2019	Feb	Feb	Feb	May	May	May
2020	Feb	Feb	Feb	No sample (COVID)	No sample (COVID)	No sample (COVID)
2021	Feb	Feb	Feb	Apr	Apr	Apr
2022	Feb	Feb	Feb	Apr	Apr	Apr
2023	Feb	Feb	Feb	Apr	Apr	Apr
2024	Apr	Apr	Apr	Oct	Oct	Oct

[A] Episodic monitoring, also shown in italics.

Buck Island Bar (BAR)

Established in 2017, this is the largest study site in the SFCN Caribbean parks, covering 99,416 square meters (24.6 ac). Located in the park's northeast, it lies on a deep reef habitat often referred to as the Buck Island Bar (Figure 3). The reef feature ranges from 27 to 41 meters (90–135 ft) depth. The BAR is the deepest site monitored by the SFCN marine program and is considered a "shallow" mesophotic reef. The reef is also dominated by *Orbicella* spp., as well as *Agaricia* spp., though corals generally have a plating morphology, a typical characteristic of low-light coral communities. Initial monitoring revealed this site possessed the highest coral cover of any SFCN monitoring location (Miller et al. 2017). Annual monitoring at the BAR included videography, disease assessment, and species richness components for all sample events (Table 1). No monitoring occurred at the BAR in 2020 due to COVID. The BAR was typically monitored around April–May, and although no episodic monitoring has occurred, the timing of monitoring shifted to October in 2024.

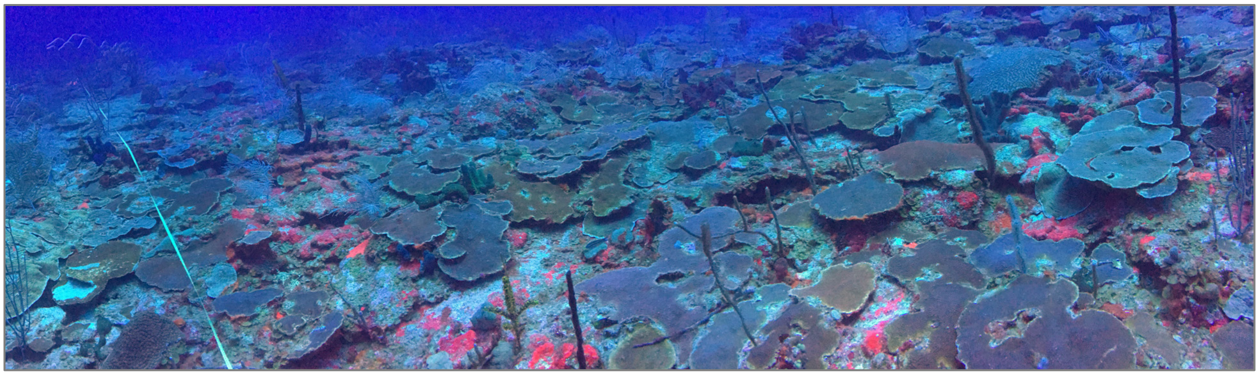

Figure 3. A typical view of the Buck Island Bar monitoring site, which is dominated by plating *Orbicella* colonies that form a dense reef terrace.
NPS / MIKE FEELEY

Survey Design and Data Collection

Monitoring activities follow the procedures described in the SFCN Coral Reef Monitoring Protocol (Miller et al. 2017). Each site consists of permanent, randomly selected 2 × 10 meter (6.6 × 32.8 ft) transects, monitored using underwater video. South Fore Reef has 20 transects, randomly distributed in a polygon that defines the reef (approximately 40,000 square meters [430,556 ft^2]). The greater area (approximately 100,000 square meters [1,076,391 ft^2]) and depth of the Buck Island Bar required a different approach due to logistical constraints: an alternative design using four subsites is used. The four subsites are randomly distributed in the polygon that defines the reef. The four transects at each subsite are oriented in the cardinal directions, do not overlap, and are placed approximately 10 meters (32.8 ft) from a center point at the subsite (16 transects total).

Stony Coral and Gorgonian Cover

Benthic cover is quantified from still frames derived from video using a point-count method. Ten random points were applied to each non-overlapping image, and the benthic category beneath each point was identified by trained observers. Percent cover of live stony corals and gorgonians is calculated at the transect level. Benthic cover (videography) data collection occurred from 2002 to 2024 at SFR and 2017 to 2024 at BAR (Table 1).

Stony Coral Species Richness

In situ species richness assessments were added in 2010, where all live stony coral species present on each transect are identified. Dead corals, even if species could be determined from the skeletal structure, were not included in species richness assessments. Species richness data collection occurred from 2010 to 2024 at SFR and 2017 to 2024 at BAR (Table 1).

Stony Coral Disease

In situ disease assessments began in 2005. The observer identifies the affected live stony coral species, discrete coral colony, and the type of disease. Disease lesions are identified as bright white areas of dead coral tissue not yet colonized with turf algae. Only live coral colonies exhibiting active disease lesions were classified as diseased. Colonies that were fully dead and lacked remaining live tissue, even if apparent mortality occurred recently from disease, were not included in the assessment. Lesion area is calculated from maximum length and perpendicular width measurements. Coral disease data were collected at SFR from 2005 to 2024; however, colony counts were not incorporated until 2010, so prevalence estimates are thus limited to 2010 onward. At the BAR, all coral disease data were collected from 2017 to 2024 (Table 1).

Water Temperature and Coral Bleaching

At each site, two replicate HOBO Pro v2 data loggers record water temperature at reef depth at two-hour intervals. The temperature records from the two loggers are averaged. At South Fore Reef, both loggers are positioned at 40 feet (12.2 meters [m]) and have recorded continuously since March 2006. To characterize temperature conditions from June 2003 through March 2006, water temperature data from a nearby location, Western Spur and Groove, is used. This site was selected as a proxy due to its similar depths (35 feet [10.7 m]) and proximity (approximately 3 kilometers [1.9 miles {mi}]) to South Fore Reef. At Buck Island Bar, both loggers are positioned at 100 feet (30.5 m) and have recorded continuously since April 2016.

Analyses

The program R version 4.4.1 (2024-06-14) was used for all statistical analyses (R Core Team 2025). Models were assessed for fit using simulation-based residual diagnostics, including tests for dispersion, autocorrelation, residual uniformity, and outliers, along with evaluation of collinearity and random-effects assumptions using the *DHARMa* package in R (Hartig 2024).

Stony Coral and Gorgonian Cover

To assess trends in coral cover that occasionally shifted in response to disturbance events, benthic cover was assessed using a breakpoint regression (Muggeo 2008). A binomial generalized linear model (GLM) was used to identify the optimal number and location of breakpoints in the trend that resulted in best fit. Competing models with different numbers of breakpoints were compared using information criteria (AIC and BIC), with preference given to simpler models unless additional breakpoints substantially improved model fit.

After breakpoints were identified, the time series was fit between breakpoints with a generalized linear mixed model (GLMM) in the binomial family. Using the *glmmTMB* and *segmented* R packages, several alternative random-effects structures were evaluated to account for different sources of variability, including: (1) random intercepts for transects and subsite (if applicable), (2) random intercepts for sample event to account for variability shared among transects sampled during the same survey, and (3) random intercepts and slopes allowing transects to change at different rates through time (Brooks et al. 2026; Muggeo 2008). Model stability was assessed by comparing Nelder-Mead and Broyden-Fletcher-Goldfarb-Shanno (BFGS) refits. First, parameter estimates were compared to ensure similarity. Second, if the maximum absolute difference in fixed-effect estimates between the refits was greater than 1, the model was considered unstable and dropped from consideration. Where appropriate, models also considered temporal correlation structures to account for autocorrelation among repeated observations.

Candidate models were compared using AIC, and model stability was evaluated by refitting models with multiple numerical optimizers. Models that produced substantially different parameter estimates across optimizers were considered unstable and were excluded from interpretation. The final model for each site was selected as the lowest-AIC model among those that met stability criteria and showed acceptable diagnostic performance based on DHARMa residual diagnostics and inspection of QQ plots. Segment-specific slopes (βSeg) were calculated as linear combinations of fixed effects after back-transforming standardized time and breakpoint terms to the original time scale.

Mean estimates are reported with a bootstrapped 95% confidence interval ($\bar{x}$, 95% CI: x_{min}–x_{max}), as the bootstrap approach provides more reliable coverage than Wald intervals when sample sizes are limited or distributions deviate from normality (Efron and Tibshirani 1993). The Buck Island Bar monitoring site uses a two-level bootstrap to calculate confidence intervals, first at the subsite level, then at the site level.

Stony Coral Species Richness

Species richness was analyzed using the same breakpoint regression framework described above for benthic cover. Segmented GLMs were first used to estimate candidate breakpoint locations (Muggeo 2008), after which the time series was fit using GLMMs (Brooks et al. 2026). Transect and subsite (if applicable) were included as random effects to account for repeated sampling through time, and alternative random-effects structures and temporal correlation structures were evaluated as described for the benthic cover analyses.

Because species richness represents count data rather than proportional cover, models were fit using count distributions rather than a binomial distribution. Conway–Maxwell Poisson (CMP) models were typically selected because they can accommodate both under- and over-dispersion and provided improved model fit relative to standard Poisson or negative binomial regressions.

Species heatmaps were used to assess changes in specific taxa among sample events. Species with high susceptibility to Stony Coral Tissue Loss Disease (SCTLD) are grouped together: *Colpophyllia natans, Dendrogyra cylindrus, Meandrina* spp*., Dichocoenia stokesii, Diploria labyrinthiformis, Eusmilia fastigiata,* and *Pseudodiploria* spp. (SCTLD Case Definition 2018). Species with intermediate (moderate) susceptibility to SCTLD are also grouped together: *Orbicella* spp., *Montastrea cavernosa, Siderastrea* spp., *Stephanocoenia intersepta,* and *Solenastrea bournoni*. Species considered to be sensitive to thermal stress are also grouped together: *Agaricia agaricites, Agaricia fragilis, Helioseris cucullata*, and *Millepora* spp. (Levas et al. 2018; Smith et al. 2013).

Some species of corals are cryptic and/or have had known problems with detection or identification in the dataset: *Agaricia fragilis, Favia fragum, Manicina areolata, Scolymia* spp*., Siderastrea radians,* and *Stylaster rosaceus*. To minimize bias in trend estimation, these taxa were excluded from trend analyses but included in the heatmap for completeness and transparency.

Disturbance Events

Although several disturbance events occurred over the duration of monitoring, episodic monitoring was not always conducted in response, occurring only when time and resources allowed. Disturbance events considered in this analysis include direct hits from major hurricanes, disease outbreaks, and bleaching from thermal stress. A timeline of notable disturbance events over the course of monitoring is available in Figure 4.

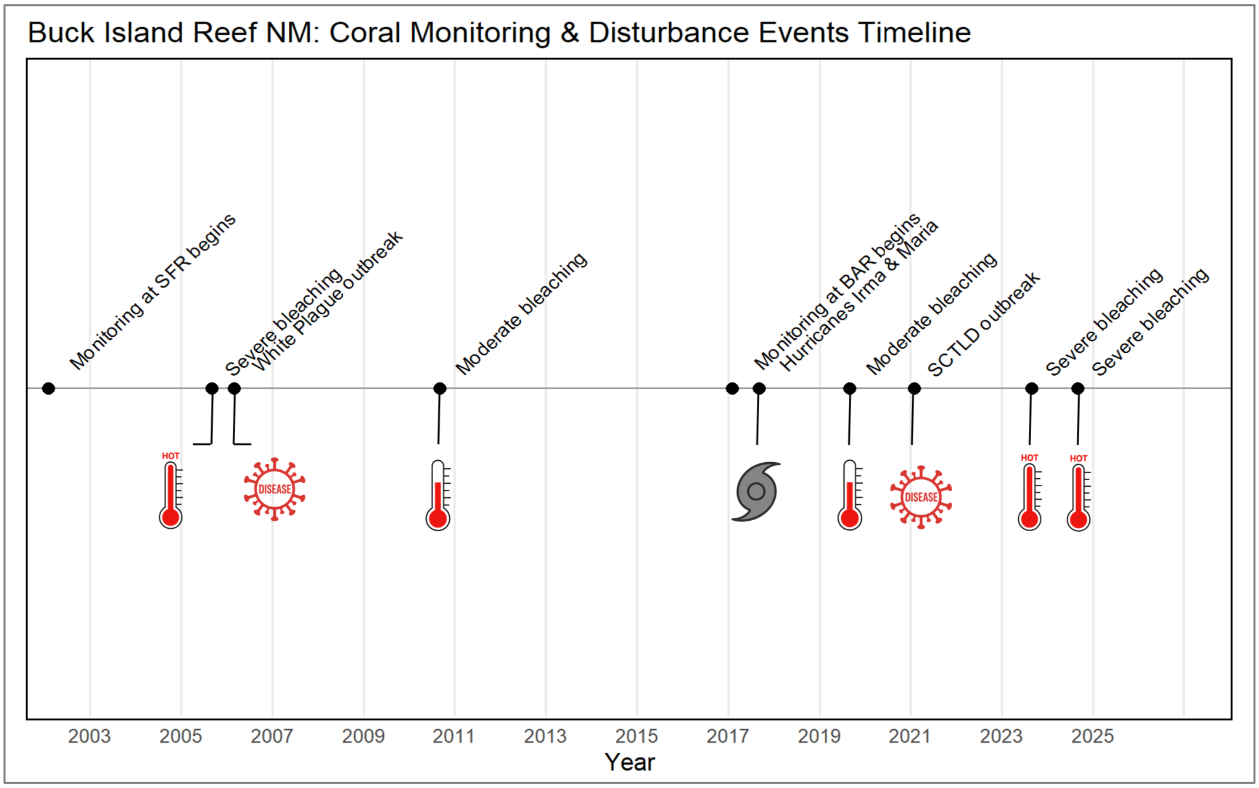

Figure 4. A timeline of significant disturbance events (hurricanes, moderate and severe bleaching events, and coral disease outbreaks) at South Fore Reef (SFR) and Buck Island Bar (BAR) coral monitoring sites in Buck Island Reef National Monument.

NPS / SFCN

Hurricanes

Only direct impacts from major hurricanes (Category 3 or higher) were considered disturbance events for this analysis, as weaker storms are less likely to produce measurable effects on benthic communities. Benthic trends were assessed to evaluate whether major storm events coincided with detectable changes in monitoring data. Wilcoxon signed-rank tests were applied to evaluate the statistical significance of abrupt changes, independent of long-term trends.

Stony Coral Disease

To assess coral disease as a disturbance that resulted in significant changes in benthic cover and/or species richness, we examined disease prevalence and severity at each site. Disease prevalence is calculated as the number of diseased stony coral colonies divided by the number of overall stony coral colonies per transect (site means). Disease prevalence is only available from 2010 onward. Disease severity is assessed as the total disease lesion area coverage per transect (site means) by disease type. Disease severity data extends back to 2005.

While there are no formally established disease prevalence thresholds for what constitutes an outbreak, for this report we consider prevalence values less than 1% as “baseline,” 1–3% as “elevated,” and greater than 3% as “outbreak” for each disease type based on similar studies (Aeby et al. 2021; Hayes et al. 2022; Page et al. 2023; Randazzo-Eisemann et al. 2022).

Water Temperature and Coral Bleaching

Thermal stress and bleaching responses are used to define disturbance events in the monitoring timeline. Thermal stress is quantified by calculating the amount of accumulated heat stress in Degree Heating Weeks (DHW), a combined measure of how much a bleaching threshold is exceeded and for how long over the previous 12 weeks. Methods follow those used in NOAA’s Coral Reef Watch (Skirving et al. 2020) but use SFCN reef-depth temperature rather than sea-surface temperatures and the established bleaching threshold of 29.5°C (85.1°F) for the U.S. Virgin Islands (Davis et al. 2025; Manzello et al. 2007a):

$$DHW_i = \sum_{n=i-83}^{i} \left(\frac{HS_n}{7}\right)$$

Where ΣHS_n is the sum of HotSpot values for n days in the 12 weeks (83 days) preceding and including date i, measured in °C above the Maximum Monthly Mean climatology. Any value greater than or equal to 1°C above the Maximum Monthly Mean is considered above the bleaching threshold (29.5°C [85.1°F] in the U.S. Virgin Islands). Only values above this bleaching threshold are included, while values less than 1°C above the Maximum Monthly Mean are set to zero.

Bleaching prevalence is calculated from video analysis as the number of points identified as coral with any bleaching observed divided by the overall number of points identified as coral on a transect. Bleaching severity is assessed visually and given a value of BL1 (severe), BL2 (substantial), BL3 (moderate), or BL4 (minor). No value is attributed to unbleached corals with no discoloration.

For this report, “severe” bleaching years are those with greater than 12 DHW that resulted in a measurable bleaching response and coincided with the NOAA threshold of Bleaching Alert Levels 3–5. “Moderate” bleaching years are those with 4–12 DHW that resulted in a measurable bleaching response and coincided with the NOAA threshold of Bleaching Alert Levels 1–2.

Bleaching prevalence and severity observations are dependent on the accumulated heat stress of the season, but also *when* monitoring occurs. Higher values are more likely if monitoring occurs near the thermal peak of the season (September or October), whereas lower values are likely if monitoring occurs near the thermal minimum (February or March). Further, if a bleaching response is observed near the thermal minimum of the season, it is likely indicative of more intense bleaching stress several months prior and the extant corals are in the process of returning to their natural coloration.

Shallow vs. Deep Site Comparison

We qualitatively compared the timing and magnitude of responses to disturbance events between South Fore Reef and Buck Island Bar. Time series were plotted together to facilitate visual assessment of similarities and differences in response over the monitoring period. The most affected species at each site were examined to provide ecological context.

Results

Stony Coral Cover

Although the duration of monitoring differs between sites, since monitoring was initiated, South Fore Reef and the Buck Island Bar have experienced a 69% and 74% loss in total stony coral cover respectively (Figure 5). In 2017, the coral cover at BAR was 31.6% (95% CI: 24.3–38.4%), about three times higher than SFR (9.0%, 95% CI: 7.4–10.8%). In 2024, declines in coral cover at both sites resulted in some of the lowest values recorded over the duration of monitoring with much more similar values of 8.2% (95% CI: 5.9–11.9%) at BAR and 5.3% (95% CI: 4.3–6.5%) at SFR.

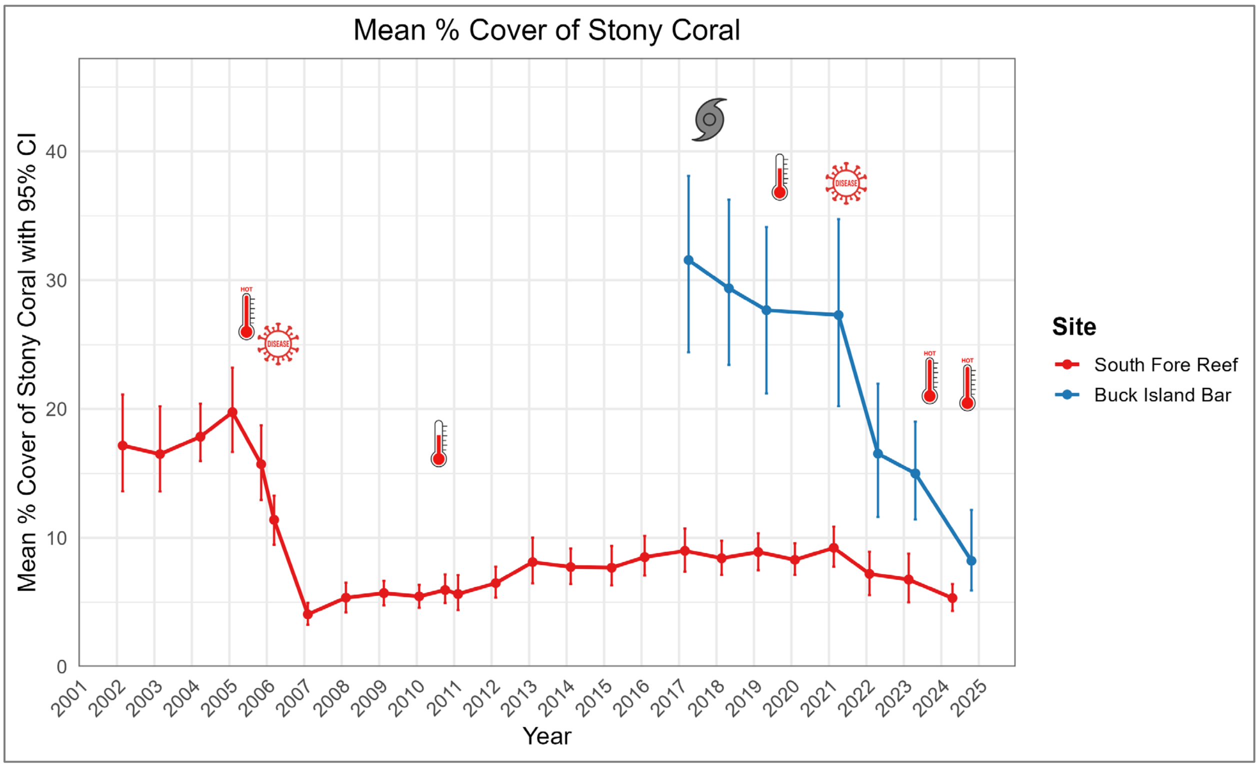

Figure 5. Mean stony coral cover at the Buck Island Bar (BAR) and South Fore Reef (SFR). Error bars are bootstrapped 95% confidence intervals. Disturbances are indicated by icons: partially filled thermometers are moderate bleaching events (2010, 2019), full thermometers are severe bleaching events (2005, 2023, 2024), hurricanes (2017), and disease outbreaks (2005, 2021).
NPS / SFCN

South Fore Reef

At South Fore Reef, the selected breakpoint model for stony coral cover included time as a fixed effect and transect as a random effect with no autoregressive structure, identifying five distinct time periods (Figure 6):

1. ***2002–2005 Stability***: Stony coral cover remained stable with no significant trend (β_{Seg1} = −0.002 log-odds yr^{-1}, p = 0.89), ranging from 17.2% (95% CI: 14.0–21.1%) in 2002 to 19.8% (95% CI: 16.7–23.0%) in 2005.
2. ***2005–2007 Rapid decline***: Stony coral cover trended significantly downward (β_{Seg2} = −1.230 log-odds yr^{-1}, p < 0.001), from 19.8% (95% CI: 16.7–23.0%) in 2005 to 4.1% (95% CI: 3.3–5.0%) in 2007.
3. ***2007–2014 Gradual growth***: This period showed gradual, steady growth of stony coral cover, increasing significantly (β_{Seg3} = 0.093 log-odds yr^{-1}, p < 0.001) from 4.1% (95% CI: 3.3–5.0%) in 2007 to 7.7% (95% CI: 6.4–9.1%) in 2014.
4. ***2014–2021 Slow growth***: Stony coral cover showed a weak but continued positive trend during this period (β_{Seg4} = 0.017 log-odds yr^{-1}, p < 0.01), increasing slightly overall from 7.7% (95% CI: 6.4–9.1%) in 2014 to 9.2% (95% CI: 7.7–10.7%) in 2021.
5. ***2021–2024 Persistent decline***: Stony coral cover showed a significant negative trend (β_{Seg5} = −0.173 log-odds yr^{-1}, p < 0.001) from 9.2% (95% CI: 7.7–10.7%) in 2021 to 5.3% (95% CI: 4.3–6.5%) in 2024.

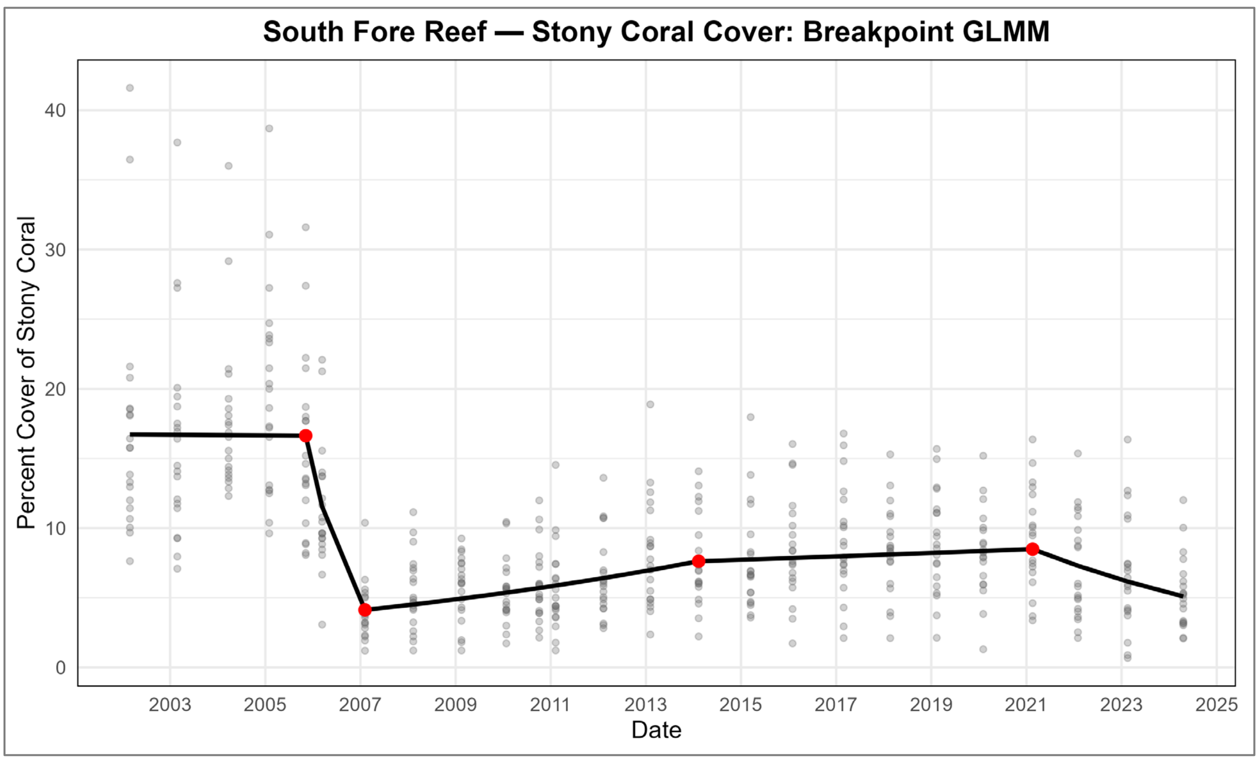

Figure 6. A breakpoint regression models mean coral cover change at South Fore Reef (SFR). A binomial GLM was used to identify the optimal number and location of breakpoints (red dots). A binomial GLMM was used to fit the model to the time series sections in between identified breakpoints (black line). Gray dots indicate the percent coral cover of individual transects during each sample event. The selected model has time as a fixed effect and transect as a random effect with no autoregressive structure.
NPS / SFCN

The coral coverage at South Fore Reef is dominated by two genera: *Orbicella* spp. and *Porites* spp. (Figure 7). The changes in these two genera contribute the most to overall trends observed in coral cover. No other coral genus had more than 1% cover over the duration of monitoring.

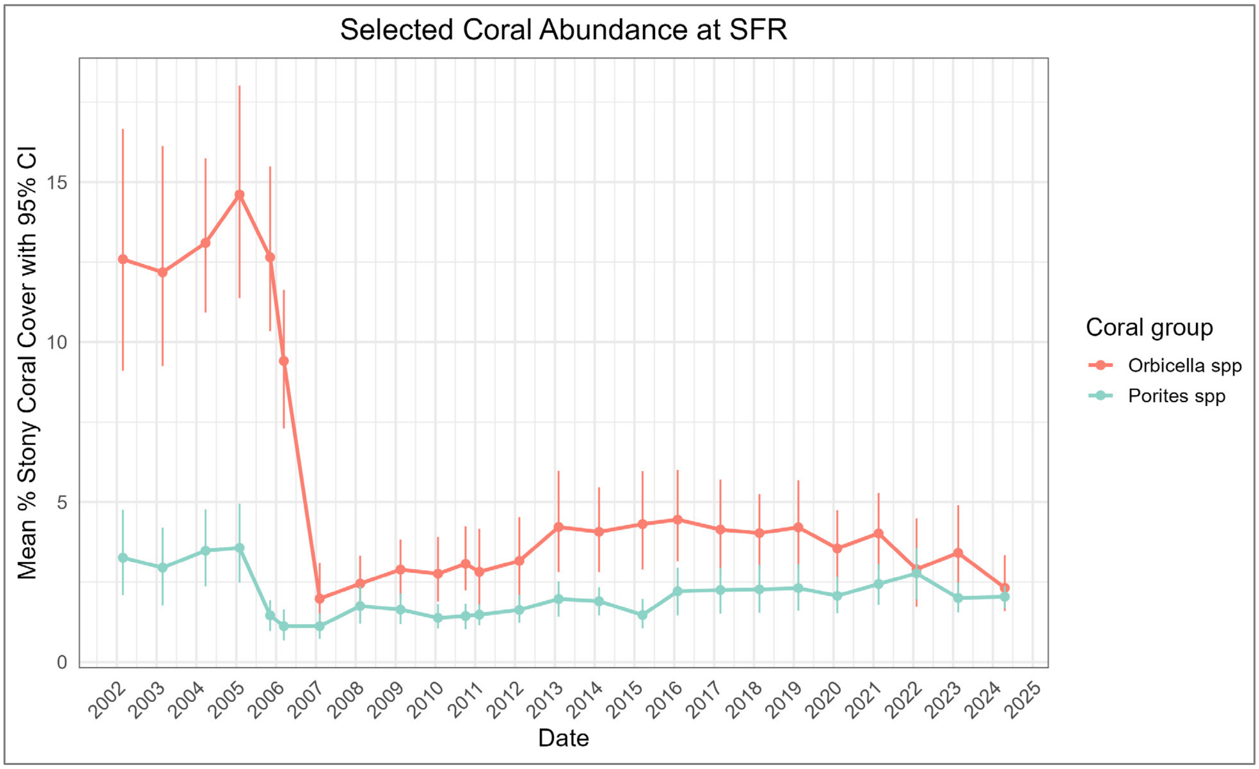

Figure 7. Mean cover of the stony coral genera, *Orbicella* and *Porites*, at South Fore Reef (SFR). Error bars are bootstrapped 95% confidence intervals.
NPS / SFCN

Buck Island Bar

At the Buck Island Bar, the selected breakpoint model included time as a fixed effect and (1) random slope and (2) transect × subsite as random effects with no autoregressive structure, identifying two distinct time periods (Figure 8):

1. ***2017–2021 Steady gradual decline***: Stony coral cover showed a significant, gradual negative trend ($\beta_{Seg1} = -0.062$ log-odds yr^{-1}, $p < 0.01$), dropping from 31.6% (95% CI: 24.2–38.6%) in 2017 to 27.3% (95% CI: 20.3–34.6%) in 2021.
2. ***2021–2024 Rapid decline***: Stony coral cover displayed a much steeper significant decline ($\beta_{Seg2} = -0.398$ log-odds yr^{-1}, $p < 0.001$) from 27.3% (95% CI: 20.3–34.6%) in 2021 to 8.2% (95% CI: 5.8–12.1%) in 2024.

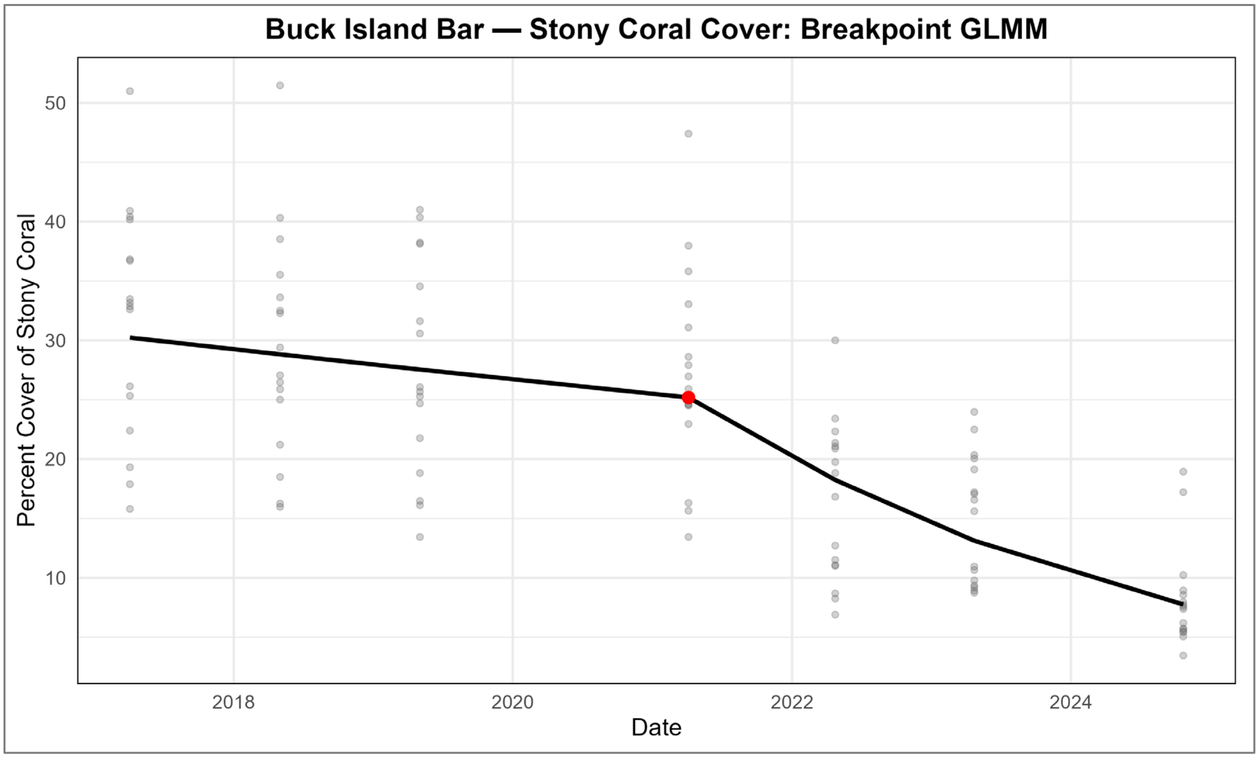

Figure 8. A breakpoint regression models mean coral cover change at Buck Island Bar (BAR). A binomial GLM was used to identify the optimal number and location of breakpoints (red dots). A binomial GLMM was used to fit the model to the time series sections in between identified breakpoints (black line). Gray dots indicate the percent coral cover of individual transects during each sample event. The selected breakpoint model has time as a fixed effect and 1) random slope and 2) transect × subsite as random effects with no autoregressive structure.

NPS / SFCN

The coral coverage at the Buck Island Bar is dominated by three genera: *Orbicella, Agaricia,* and *Porites* (Figure 9). The changes in these three genera contribute the most to overall trends observed in coral cover. No other coral genus had more than 1% cover over the duration of monitoring.

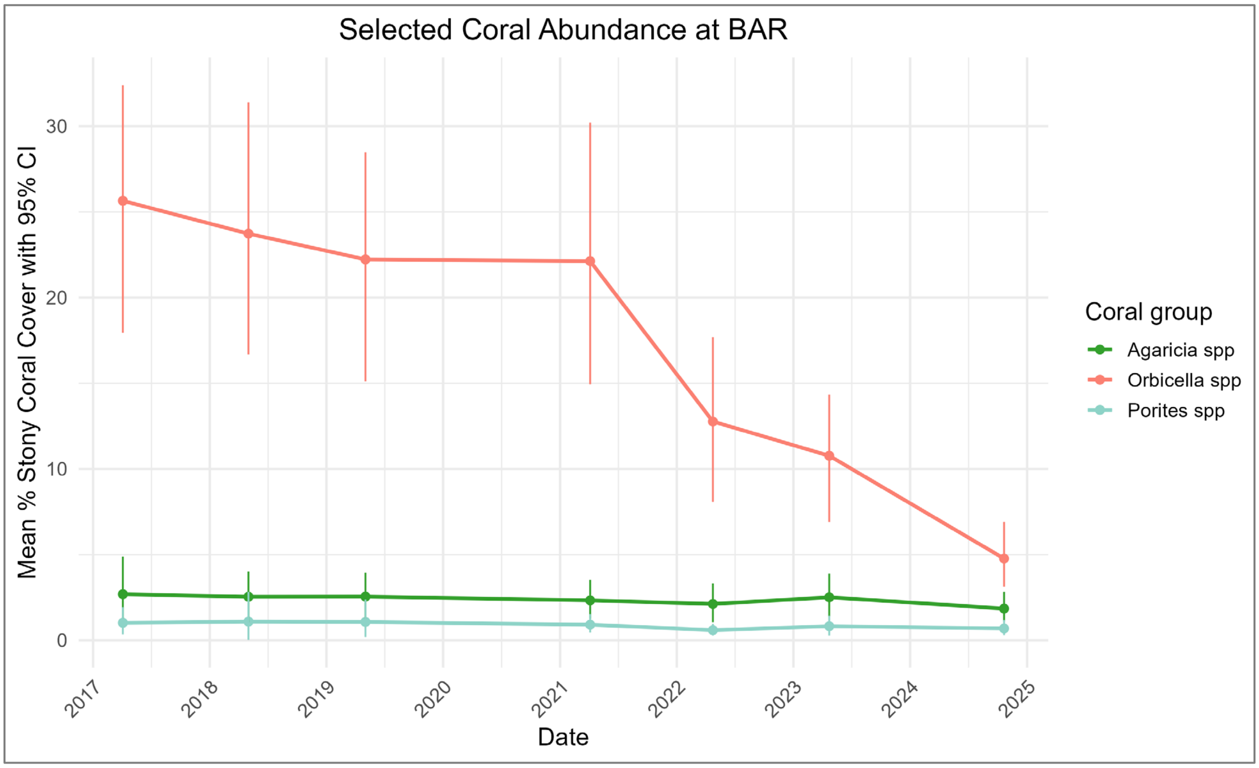

Figure 9. Mean cover of the stony coral genera, *Orbicella*, *Agaricia*, and *Porites*, at Buck Island Bar (BAR). Error bars are bootstrapped 95% confidence intervals.
NPS / SFCN

Gorgonian Cover

Gorgonian cover has remained mostly stable over the duration of monitoring at South Fore Reef and the Buck Island Bar (Figure 10).

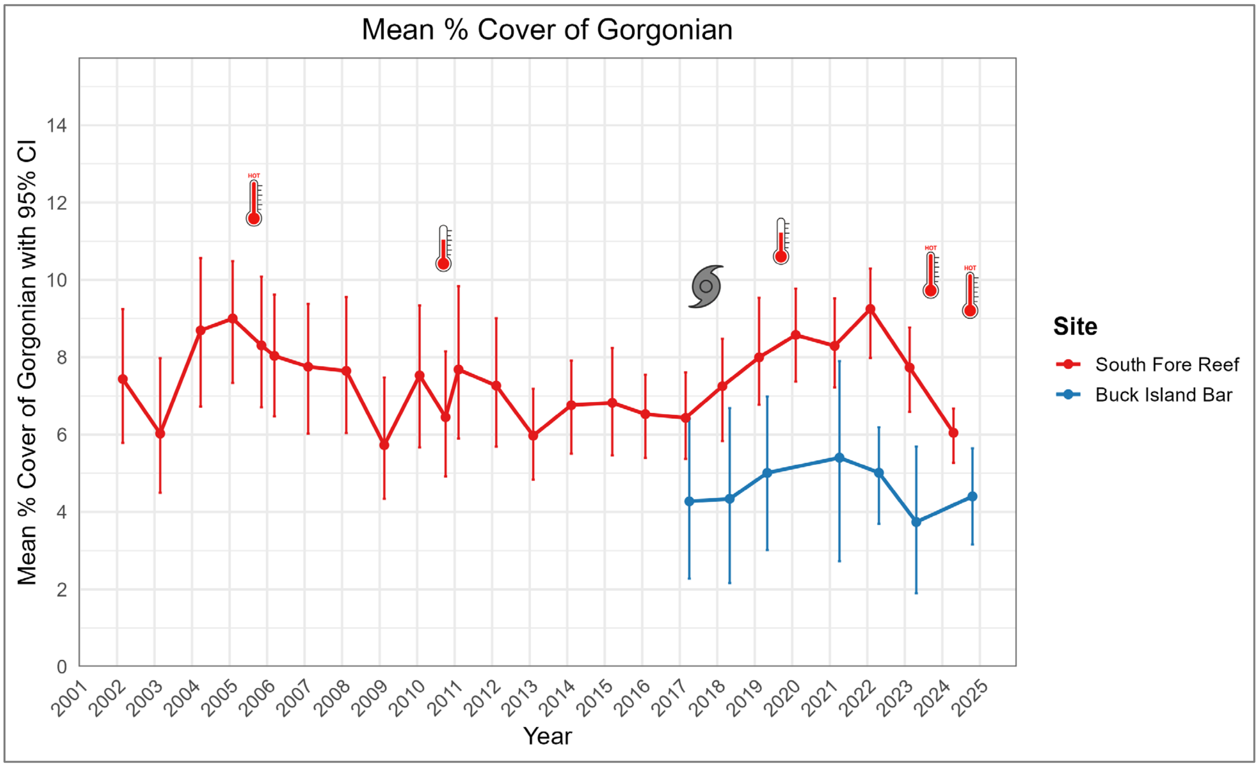

Figure 10. Mean gorgonian cover at the Buck Island Bar (BAR) and South Fore Reef (SFR). Error bars are bootstrapped 95% confidence intervals. Disturbances are indicated by icons: partially filled thermometers are moderate bleaching events (2010, 2019), full thermometers are severe bleaching events (2005, 2023, 2024) and hurricanes (2017). The coral disease outbreaks in 2005 and 2021 only affected stony corals, not gorgonians, and are omitted from this figure.

NPS / SFCN

South Fore Reef

Between 2002 and 2024, mean gorgonian cover remained within a narrow range of 5.7% (95% CI: 4.2–7.3%) to 9.3% (95% CI: 8.0–10.4%), with little change over the full monitoring period. At South Fore Reef, the selected breakpoint model for gorgonians included time as a fixed effect and (1) random slope and (2) transect as random effects with no autoregressive structure, identifying three time periods (Figure 11):

1. ***2002–2016 Stable:*** Gorgonian cover remained stable with no significant trend ($\beta_{Seg1} = -0.009$ log-odds yr^{-1}, $p = 0.16$), ranging from 7.4% (95% CI: 5.7–9.2%) to 6.5% (95% CI: 5.5–7.6%).
2. ***2016–2022 Growth***: There was a significant, increasing trend in gorgonian cover ($\beta_{Seg2} = 0.065$ log-odds yr^{-1}, $p < 0.001$) from 6.5% (95% CI: 5.5–7.6%) in 2016 to 9.3% (95% CI: 8.0–10.4%) in 2022.

3. ***2022–2024 Decline***: Gorgonian cover significantly declined from 9.3% (95% CI: 8.0–10.4%) in 2022 to 6.1% (95% CI: 5.3–6.7%) in 2024 ($\beta_{Seg3} = -0.205$ log-odds yr^{-1}, $p < 0.001$).

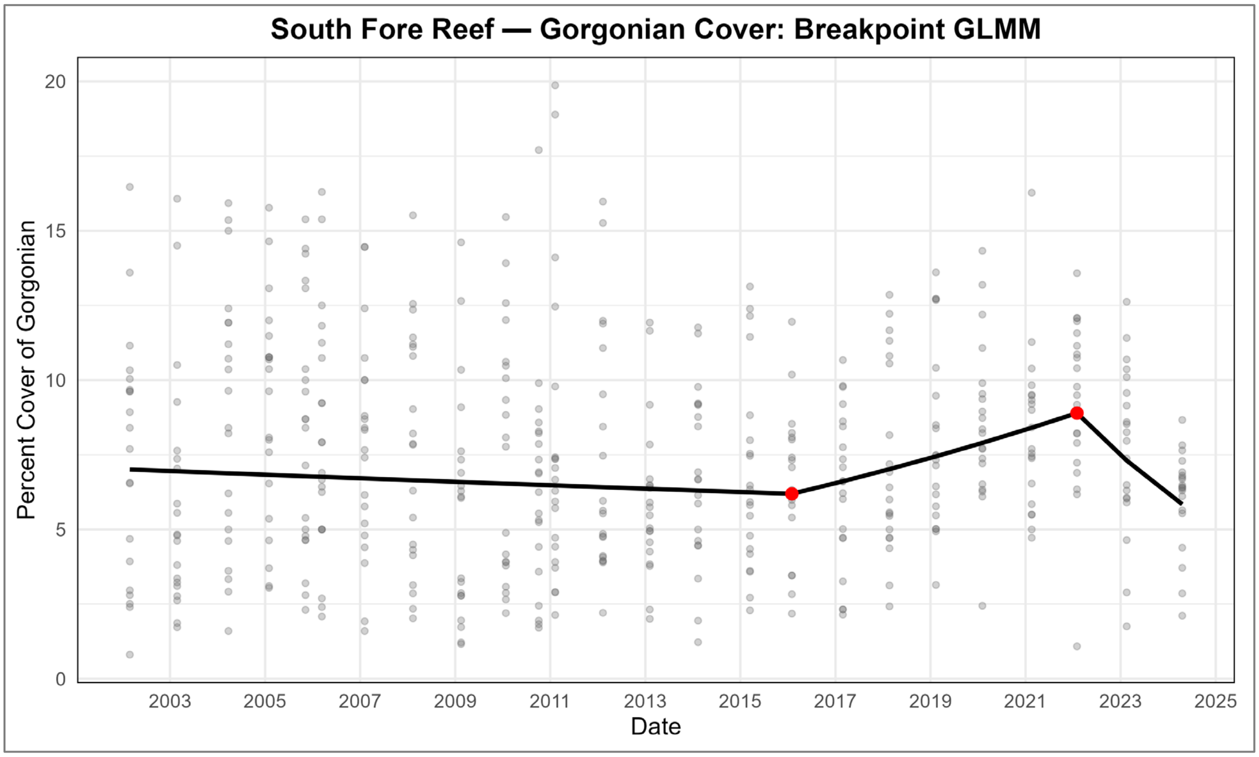

Figure 11. A breakpoint regression models mean gorgonian cover change at South Fore Reef (SFR). A binomial GLM was used to identify the optimal number and location of breakpoints (red dots). A binomial GLMM was used to fit the model to the time series sections in between identified breakpoints (black line). Gray dots indicate the percent coral cover of individual transects during each sample event. The selected breakpoint model has time as a fixed effect and (1) random slope and (2) transect as random effects with no autoregressive structure.

NPS / SFCN

Buck Island Bar

Between 2017 and 2024, mean gorgonian cover remained within a narrow range between 3.7% (95% CI: 1.9–5.7%) and 5.4% (95% CI: 2.8–8.1%), with little change over the full monitoring period. At Buck Island Bar, the selected breakpoint model for gorgonians included time as a fixed effect and 1) random slope and 2) transect × subsite as random effects with no autoregressive structure, identifying two time periods (Figure 12):

1. ***2017–2019 Slight growth:*** There was a significant, but slight, increasing trend in gorgonian cover ($\beta_{Seg1} = 0.163$ log-odds yr^{-1}, $p < 0.001$) from 4.3% (95% CI: 2.2–6.6%) to 5.0% (95% CI: 3.0–7.4%).
2. ***2019–2024 Stable***: Gorgonian cover was stable between 2019 and 2024, with no significant trend ($\beta_{Seg2} = -0.020$ log-odds yr^{-1}, $p = 0.49$), ranging from 3.7% (95% CI: 1.9–5.7%) to 5.4% (95% CI: 2.8–8.1%).

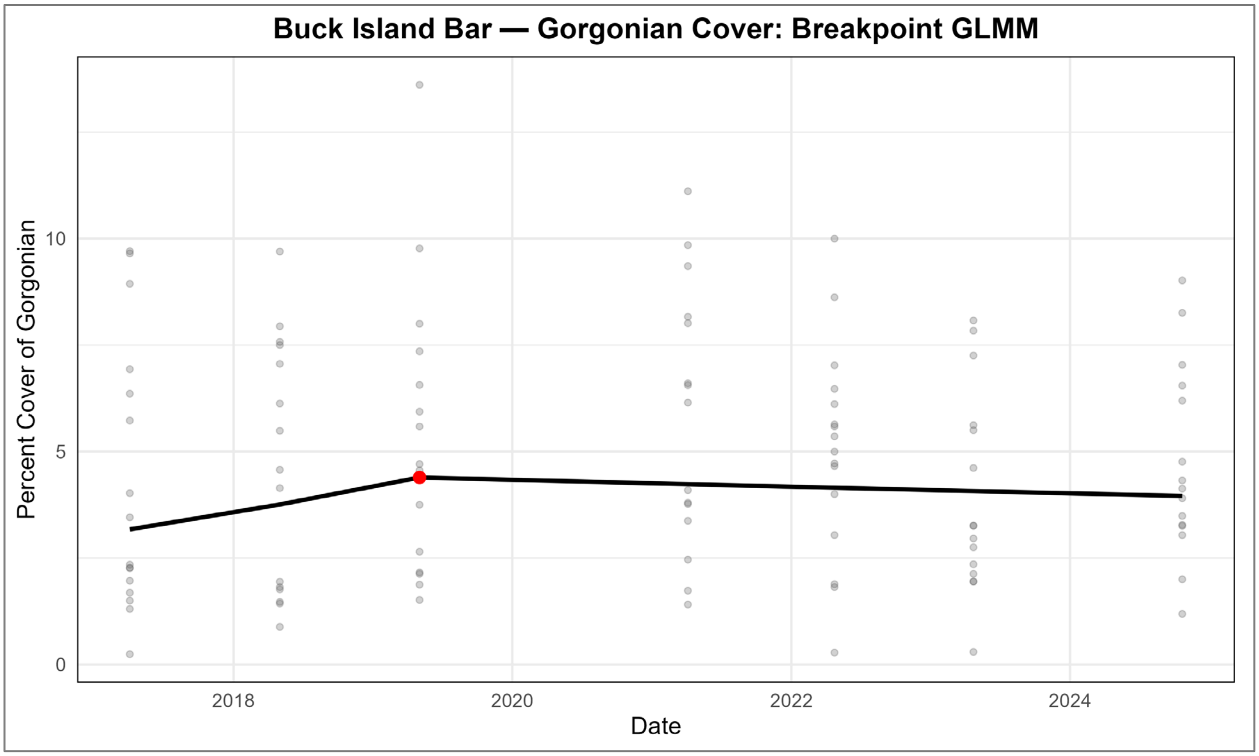

Figure 12. A breakpoint regression models mean gorgonian cover change at Buck Island Bar (BAR). A binomial GLM was used to identify the optimal number and location of breakpoints (red dots). A binomial GLMM was used to fit the model to the time series sections in between identified breakpoints (black line). Gray dots indicate the percent coral cover of individual transects during each sample event. The selected breakpoint model has time as a fixed effect and (1) random slope and (2) transect × subsite as random effects with no autoregressive structure.

NPS / SFCN

Stony Coral Species Richness

South Fore Reef and the Buck Island Bar experienced declines in mean species richness of stony coral per transect (34% and 16% respectively) over the duration of monitoring (Figure 13).

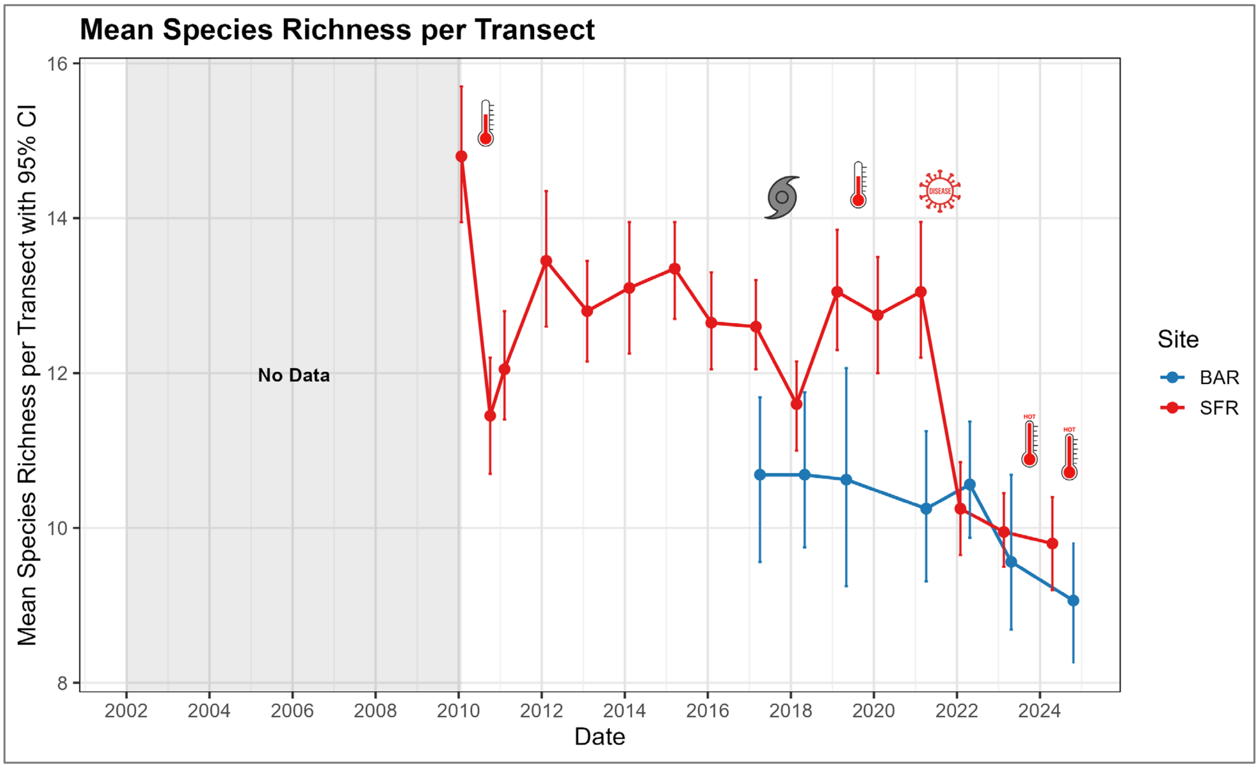

Figure 13. Mean species richness per transect at South Fore Reef (SFR, red) and Buck Island Bar (BAR, blue). Error bars are bootstrapped 95% confidence intervals. Disturbances are indicated by icons: partially filled thermometers are moderate bleaching events (2010, 2019), full thermometers are severe bleaching events (2023), hurricanes (2017), and disease outbreaks (2021). Note that species richness data was not collected at SFR from 2002 to 2009.

NPS / SFCN

South Fore Reef

At South Fore Reef, the selected breakpoint model included time as a fixed effect and transect as a random effect with no autoregressive structure, identifying three distinct time periods (Figure 14):

1. ***Jan 2010–Oct 2010 Significant decline***: Stony coral species richness exhibited a significant, sharp decline ($\beta_{Seg\ 1} = -0.209$ log-richness yr^{-1}, $p < 0.05$), ranging from 13.5 species per transect (95% CI: 12.7–14.2) in January 2010 to 11.0 species per transect (95% CI: 10.2–11.7) in October 2010.

2. ***Oct 2010–2020 Stable***: Stony coral species richness appeared stable, with no significant trend ($\beta_{Seg\ 2} = 0.006$ log-richness yr^{-1}, $p = 0.26$), ranging from 11.0 species per transect (95% CI: 10.2–11.7) in October 2010 to 12.0 species per transect (95% CI: 11.4–12.7) in 2020.

3. ***2020–2024 Significant decline***: Stony coral species richness displayed a significant, sharp decline ($\beta_{Seg\ 3} = -0.083$ log-richness yr^{-1}, $p < 0.001$) from 12.0 species per transect (95% CI: 11.4–12.7) in 2020 to 9.2 species per transect (95% CI: 8.7–9.8) in 2024.

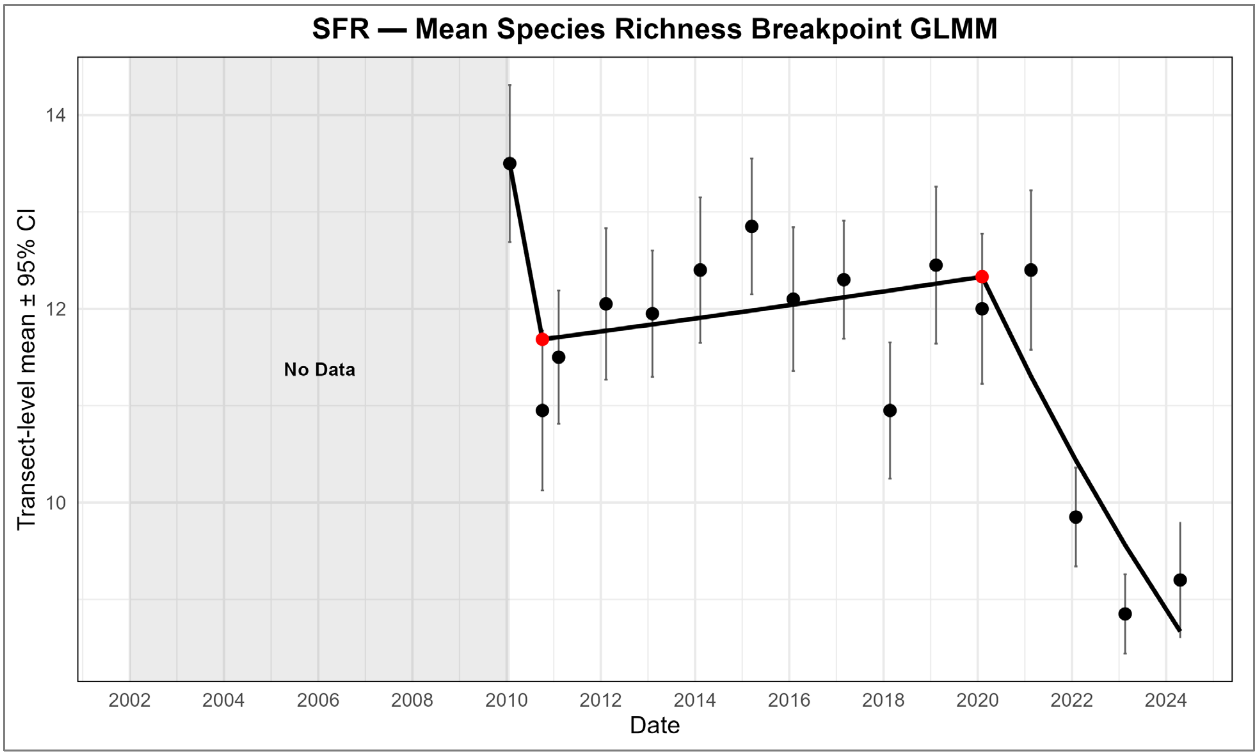

Figure 14. A breakpoint regression models transect-level mean species richness change at South Fore Reef (SFR). A GLM was used to identify the optimal number and location of breakpoints (red dots). A Conway-Maxwell Poisson GLMM was used to fit the model to the time series sections in between identified breakpoints (black line). The selected model has time as a fixed effect and transect as a random effect with no autoregressive structure. Error bars represent bootstrapped 95% confidence intervals. Species richness data was not collected at SFR until 2010 and is absent from early monitoring at the site.
NPS / SFCN

The heatmap in Figure 15 displays the percent of transects where individual stony coral species were recorded. In 2011, following the 2010 bleaching event, *Scolymia* spp. (SCOL), *Dichocoenia stokesii* (DSTO), and *Helioseris cucullata* (HCUC) experienced the most net loss. A year later the *Agaricia fragilis (*AFRA), *Scolymia* spp. (SCOL), and *Pseudodiploria strigosa* (PSTR) had the greatest net gains.

In 2022, following the outbreak of SCTLD, notable losses occurred in the following species: *Montastrea cavernosa* (MCAV), *Colpophyllia natans* (CNAT), *Meandrina meandrites* (MMEA), *Eusmilia fastigiata* (EFAS), *Diploria labyrinthiformis* (DLAB), and *Dichocoenia stokesii* (DSTO).

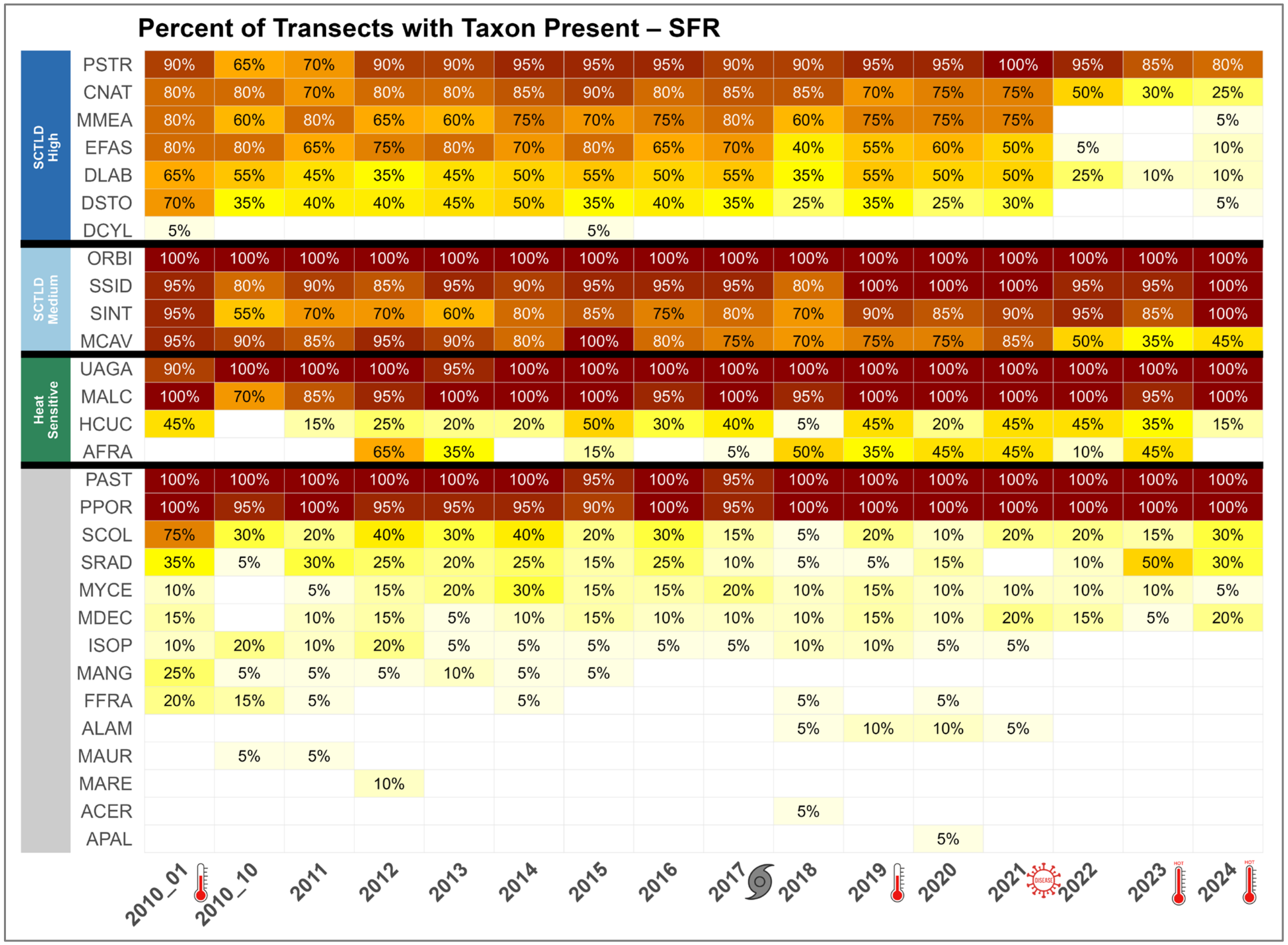

Figure 15. A heatmap displaying the percentage of transects at South Fore Reef (SFR; total transects = 20) where stony coral species were present, with darker shading indicating a higher percentage. Species that are highly susceptible to Stony Coral Tissue Loss Disease (SCTLD) are grouped with a blue bar at the left. Species with moderate susceptibility to SCTLD are grouped with a light blue bar. Species that tend to be heat sensitive are grouped with a green bar. Coral species codes are available in Appendix A. Disturbances are indicated by icons: partially filled thermometers are moderate bleaching events (2010, 2019), full thermometers are severe bleaching events (2023, 2024), hurricanes (2017), and disease outbreaks (2021). Note that species richness data was not collected at SFR from 2002 to 2009. Tabular data shown in this figure are presented in Appendix B, Table 4.

NPS / SFCN

Buck Island Bar

At the Buck Island Bar, the selected breakpoint model included time as a fixed effect and transect × subsite as a random effect with no autoregressive structure, identifying two distinct time periods (Figure 16):

1. ***2017–2022 Stable***: Stony coral species richness appeared stable, with no significant trend ($\beta_{Seg\ 1} = -0.009$ log-richness yr^{-1}, $p = 0.28$), ranging from 10.4 species per transect (95% CI: 9.4–11.3) in 2017 to 10.3 species per transect (95% CI: 9.7–10.9) in 2022.
2. ***2022–2024 Rapid decline***: Stony coral species richness displayed a significant decline ($\beta_{Seg\ 2} = -0.061$ log-richness yr^{-1}, $p < 0.001$) from 10.3 species per transect (95% CI: 9.7–10.9) in 2022 to 8.8 species per transect (95% CI: 8.1–9.4) in 2024.

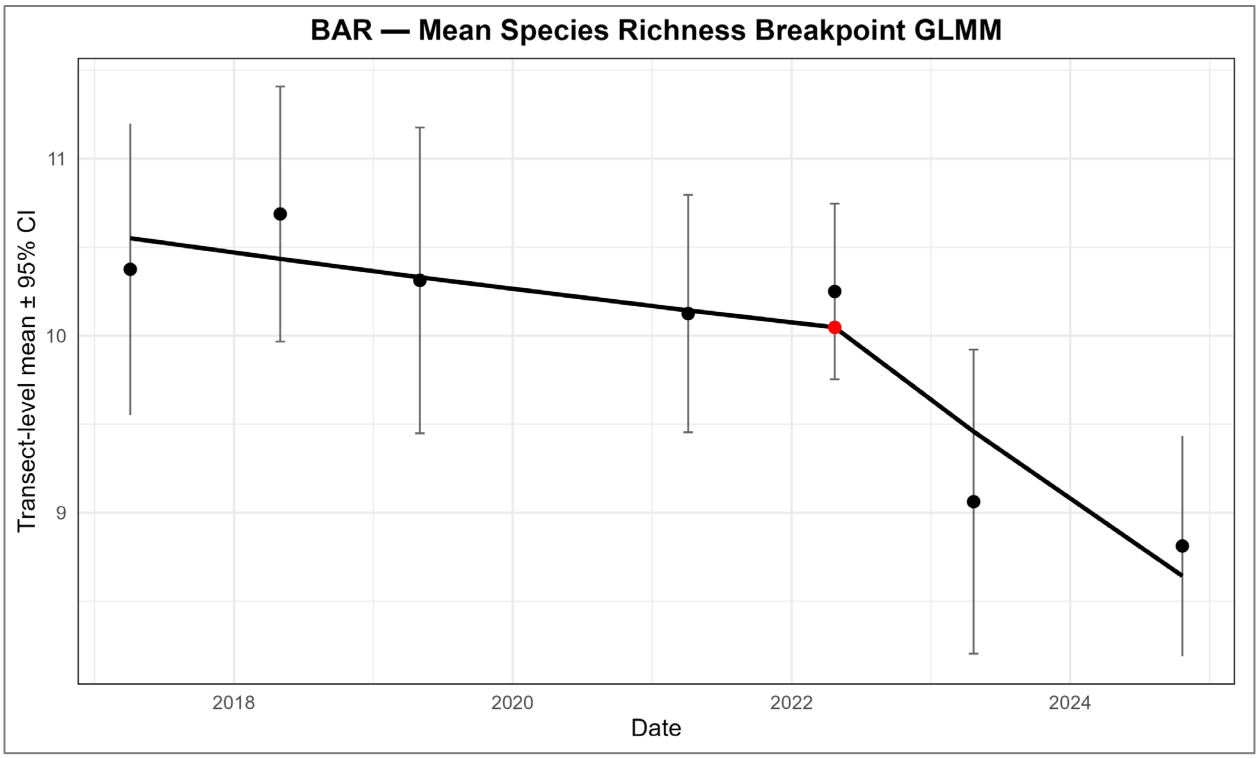

Figure 16. A breakpoint regression models transect-level mean species richness change at Buck Island Bar (BAR). A GLM was used to identify the optimal number and location of breakpoints (red dots). A Conway-Maxwell Poisson GLMM was used to fit the model to the time series sections in between identified breakpoints (black line). The selected model has time as a fixed effect and transect × subsite as a random effect with no autoregressive structure. Error bars represent bootstrapped 95% confidence intervals.

NPS / SFCN

The heatmap in Figure 17 displays the percent of transects where individual stony coral species were recorded. In 2022, following the outbreak of SCTLD, *Meandrina meandrites* (MMEA) and *Eusmilia fastigiata* (EFAS) were not recorded on a single transect and have not been recorded since.

In 2023, *Pseudodiploria strigosa* (PSTR) was absent from all transects and the corals *Montastrea cavernosa* (MCAV) and *Colpophyllia natans* (CNAT) were recorded on fewer transects than previous years.

In 2024, *Mycetophyllia* spp. (MYCE) and *Helioseris cucullata* (HCUC) were not recorded on a single transect. However, the percentage of transects where *Madracis decactis* (MDEC) and *Porites porites* (PPOR) were observed increased over the duration of monitoring.

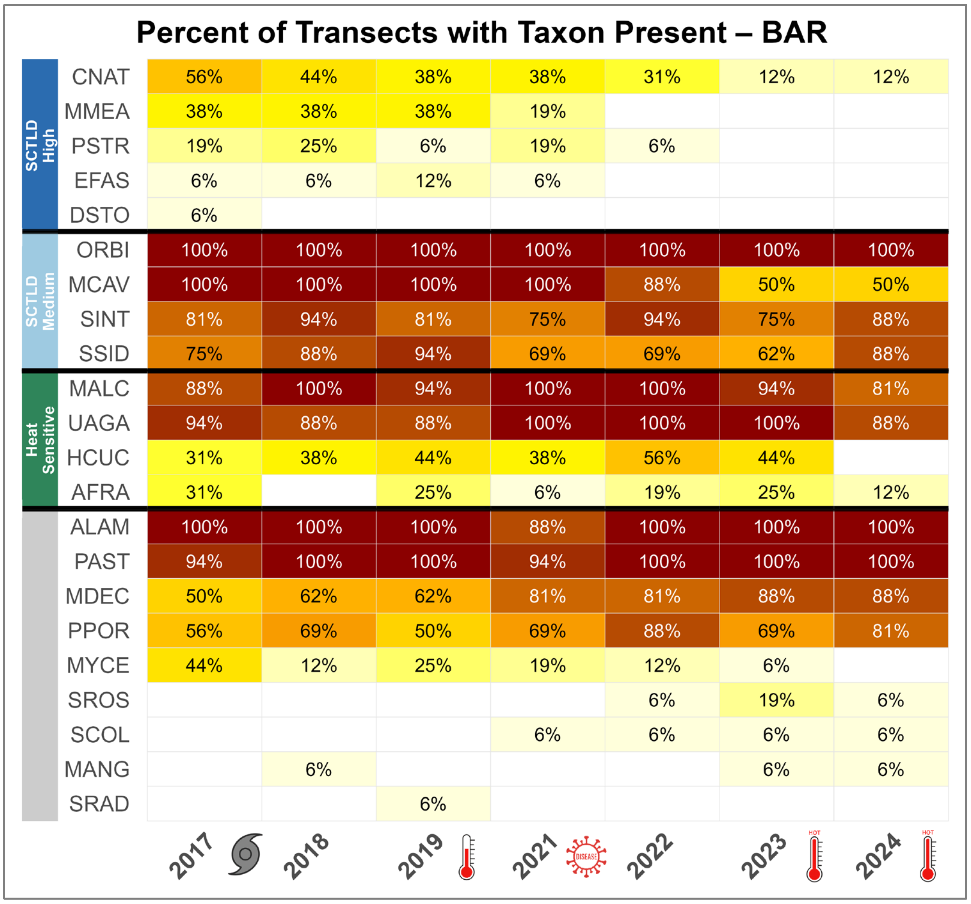

Figure 17. A heatmap displaying the percentage of transects at Buck Island Bar (BAR) where stony coral species were present. Species that are highly susceptible to Stony Coral Tissue Loss Disease (SCTLD) are grouped with a blue bar at the left. Species with moderate susceptibility to Stony Coral Tissue Loss Disease are grouped with a light blue bar. Species that tend to be heat sensitive are grouped with a green bar. On the color ramp, dark red indicates 100% transect coverage, yellow as 5% coverage, and white as absent. The percentage of transects at a site (BAR total = 16) where the species was observed is presented in each cell. The coral species listed use four-letter species codes where the first letter is the genus and next three letters are species. The full list of species codes is available in Appendix A. Disturbances are indicated by icons: partially filled thermometers are moderate bleaching events (2019), full thermometers are severe bleaching events (2023, 2024), hurricanes (2017), and disease outbreaks (2021). Tabular data shown in this figure are presented in Appendix B, Table 5.
NPS / SFCN

Disturbance Events

Hurricanes

Since 2002 when coral monitoring was initiated at South Fore Reef, the only hurricanes assessed as disturbance events occurred in 2017: Hurricane Irma (Category 5) and Hurricane Maria (Category 5). No significant changes in stony coral cover (Figure 5) nor gorgonian cover (Figure 10) at either site were detected in association with Hurricanes Irma or Maria. No significant change in species richness occurred at Buck Island Bar in 2017 (Figure 13). However, a detectable decline ($p < 0.001$, $V = 20.5$) in species richness occurred at South Fore Reef in 2018, followed by a significant rebound in 2019 ($p = 0.002$, $V = 152$). The stony coral species *Helioseris cucullata* (HCUC) and *Eusmilia fastigiata* (EFAS) experienced the greatest net loss while *Agaricia fragilis* (AFRA) experienced a net gain in 2018 (Figure 15). One year later, *Helioseris cucullata* (HCUC) experienced the biggest net gain.

Stony Coral Disease

Among the coral diseases recorded at South Fore Reef and Buck Island Bar, White Plague (WPL) and Stony Coral Tissue Loss Disease (SCTLD) accounted for most of the observed lesions. Other tissue-loss coral diseases (Yellow Band, Black Band, White Band, and White Pox) were recorded infrequently and at such low levels (≤ 0.1% prevalence) they are not reported here.

<u>South Fore Reef</u>

Two significant disease outbreaks have occurred at the South Fore Reef over the duration of monitoring (Figure 18):

1. In late 2005, a WPL outbreak began at South Fore Reef. Colony counts were not conducted until 2010, so no prevalence data exists for that event. Mean total lesion area per transect increased rapidly from 16.0 square centimeters (95% CI: 9.5–22.4 cm^2) in 2005 to a peak of 429.6 square centimeters (95% CI: 284.7–605.1 cm^2) in 2006, before waning in 2007 to 88.8 square centimeters (95% CI: 32.1–175.4 cm^2) and returning to background levels in 2008.
2. SCTLD was recorded at South Fore Reef during monitoring in January 2022. Mean total lesion area per transect spiked at 82.9 square centimeters (95% CI: 48.7–129.8 cm^2), before increasing to 109.0 square centimeters (95% CI: 31.5–213.8 cm^2) in 2023, then waning to 12.5 square centimeters (95% CI: 2.0–23.0 cm^2) in 2024. Prevalence peaked in 2022 at 4.8% (95% CI: 3.8–5.7%).

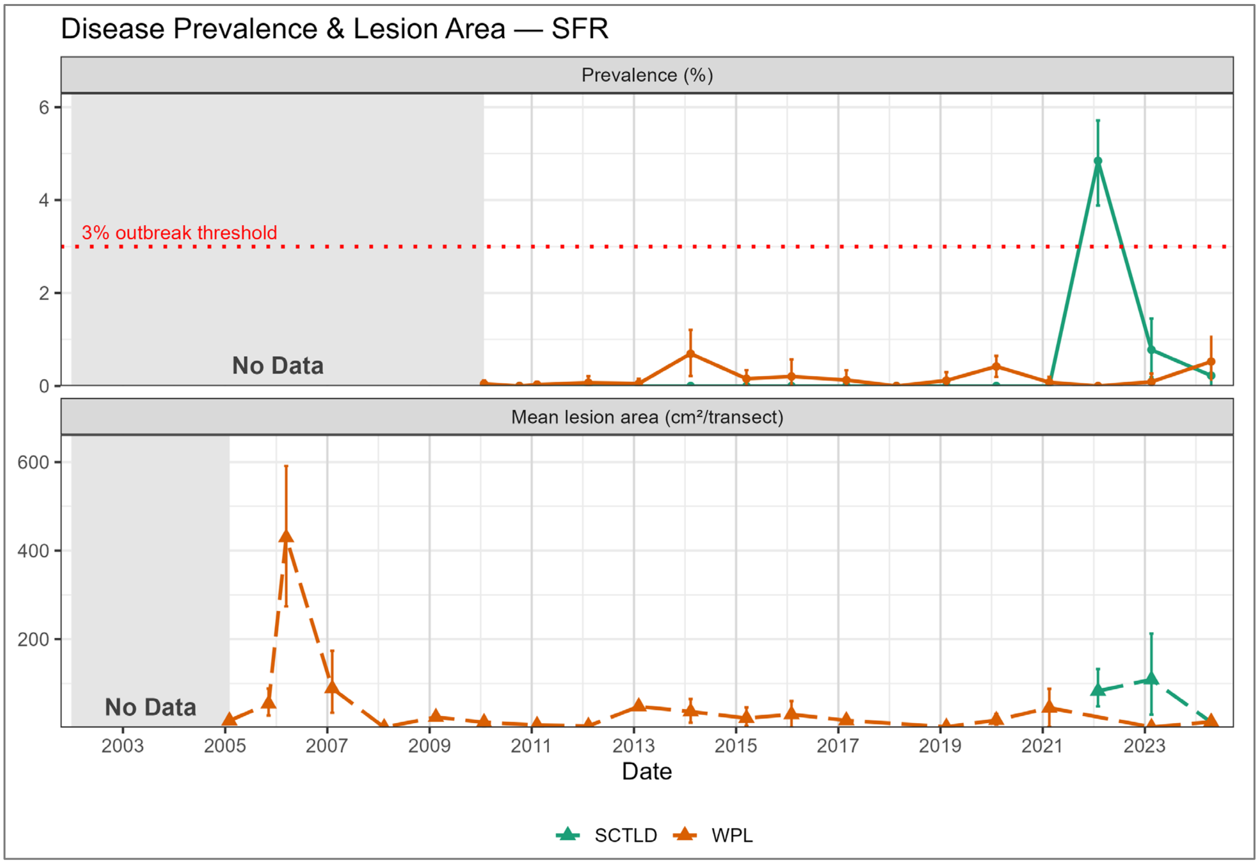

Figure 18. Disease prevalence (%, top) and mean lesion area (cm[2] per transect, bottom) for selected coral diseases at South Fore Reef (SFR). Lines show the mean value across transects during each sampling event by disease type: Stony Coral Tissue Loss Disease (SCTLD) = green, White Plague (WPL) = orange. Error bars are bootstrapped 95% confidence intervals. In the top plot, prevalence (solid line, circles) represents the percentage of coral colonies with signs of disease on each transect. The red dotted line indicates the 3% prevalence threshold used to identify disease outbreaks. In the bottom plot, mean lesion area (dashed line, triangles) represents the average total lesion area observed per transect. Gray shaded regions labeled "No Data" indicate periods prior to the start of disease monitoring for that metric.
NPS / SFCN

Buck Island Bar

While not considered an outbreak, elevated prevalence of WPL was observed at the Buck Island Bar in 2018 (1.1%, 95% CI: 0.5–1.9%), 2019 (1.8%, 95% CI: 1.0–2.8%), and 2024 (1.7%, 95% CI: 0.6–2.9%). One significant disease outbreak (i.e., SCTLD) has been recorded at the Buck Island Bar, with higher overall prevalence and severity than at South Fore Reef (Figure 19):

1. SCTLD was observed at the Buck Island Bar during monitoring in April 2021, where mean total lesion area per transect spiked at 156.8 square centimeters (95% CI: 80.4–236.4 cm^2), then increased to 344.7 square centimeters (95% CI: 110.1–731.2 cm^2) in 2022 before waning to 183.9 square centimeters (95% CI: 78.9–313.3 cm^2) in 2023, then further dropping

to 59.0 square centimeters (95% CI: 18.0–100.0 cm^2) in 2024. Prevalence followed a similar trend, peaking in 2023 at 12.6% (95% CI: 8.3–17.3%).

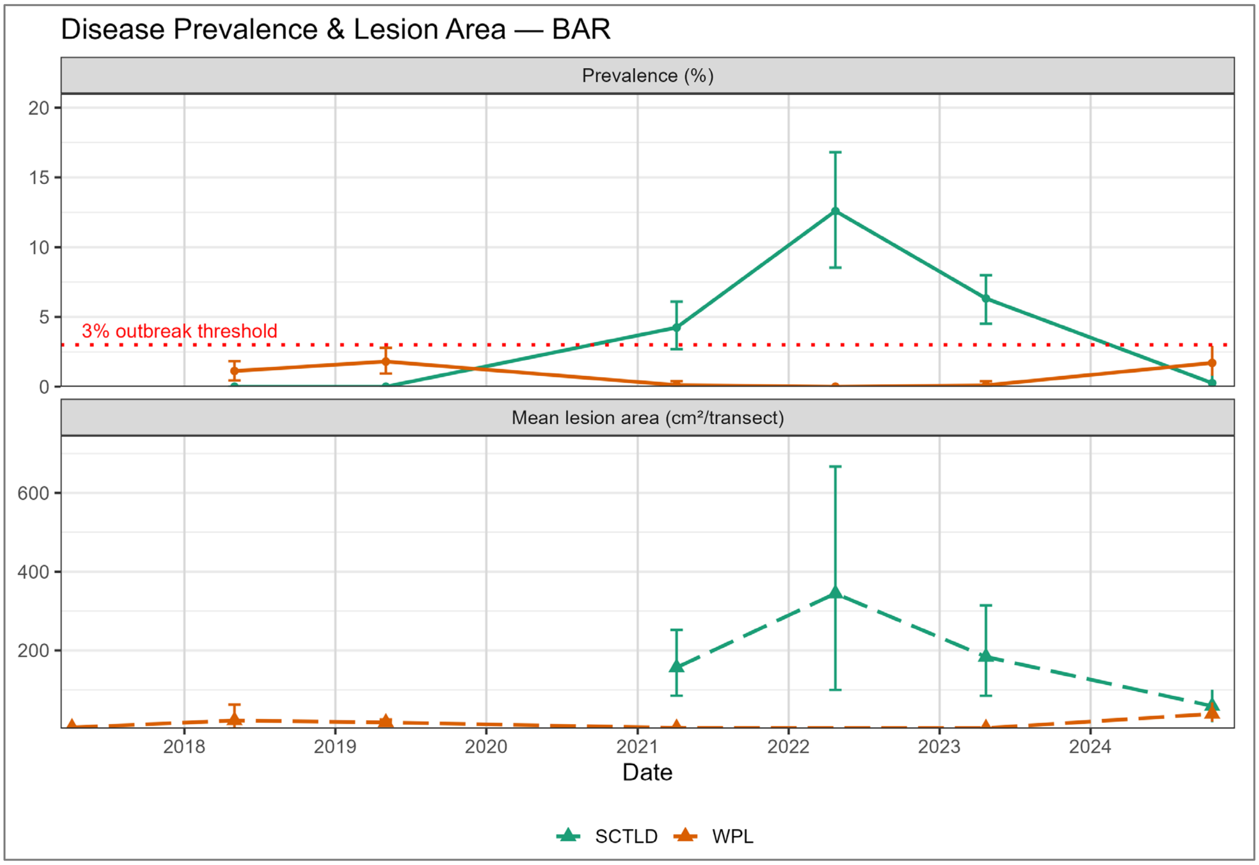

Figure 19. Disease prevalence (%, top) and mean lesion area (cm^2 per transect, bottom) for selected coral diseases at Buck Island Bar (BAR). Lines show the mean value across transects during each sampling event by disease type: Stony Coral Tissue Loss Disease (SCTLD) = green, White Plague (WPL) = orange. Error bars are bootstrapped 95% confidence intervals. In the top plot, prevalence (solid line, circles) represents the percentage of coral colonies with signs of disease on each transect. The red dotted line indicates the 3% prevalence threshold used to identify disease outbreaks. In the bottom plot, mean lesion area (dashed line, triangles) represents the average total lesion area observed per transect. *NPS / SFCN*

Water Temperature and Coral Bleaching

At South Fore Reef and the Buck Island Bar monitoring sites, water temperatures typically reach their seasonal highs in September and October and seasonal lows between February and March. Figure 20 shows the average daily temperatures of severe bleaching years 2023 and 2024, with the seasonal temperature range of non-bleaching years and the bleaching threshold of 29.5°C (85.1°F).

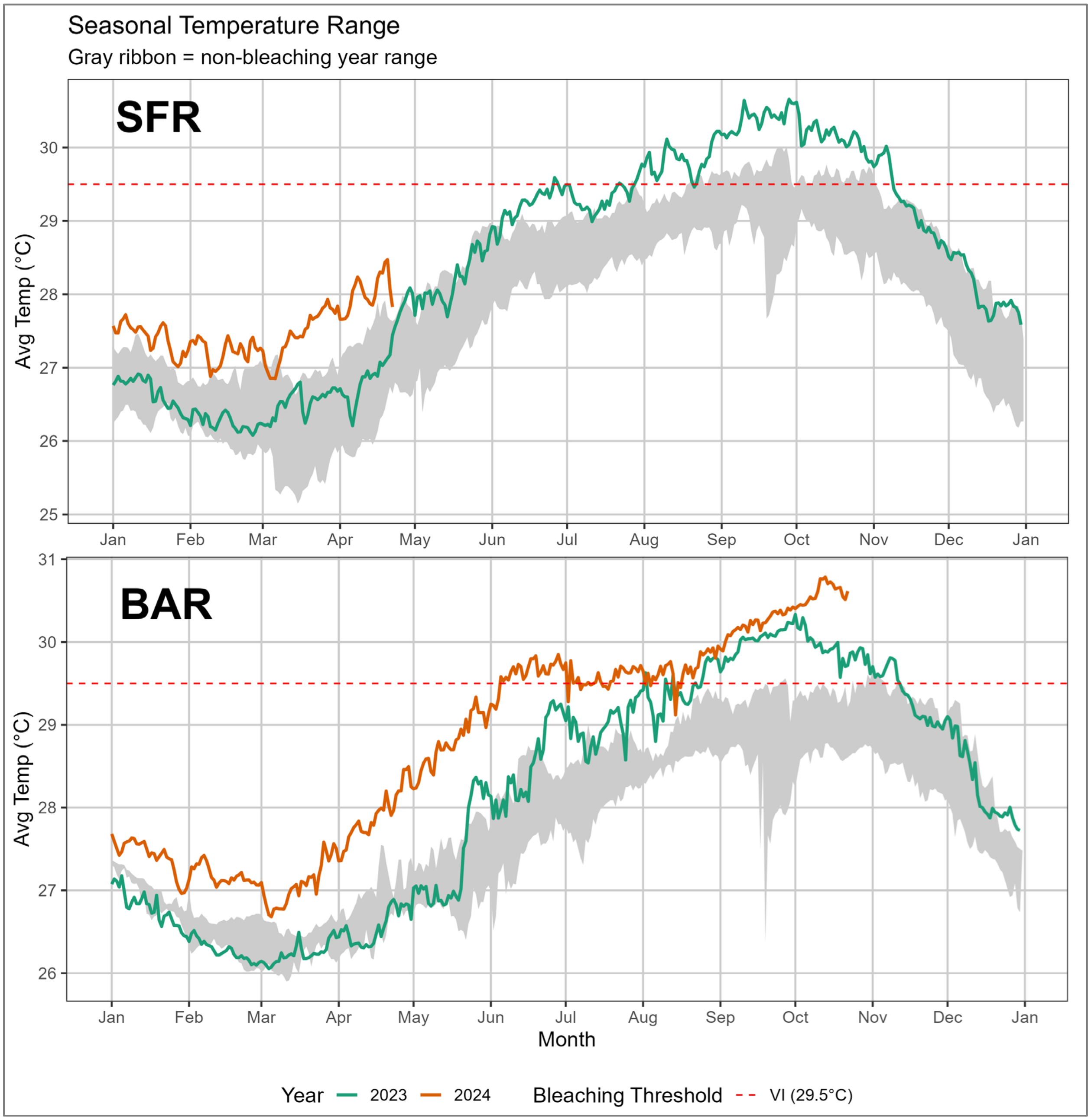

Figure 20. The average daily temperature during the severe bleaching years 2023 (green) and 2024 (orange). The gray ribbon shows the seasonal temperature range of non-bleaching years (2004, 2007–09, 2011–12, 2014, 2017–18, 2022) over the duration of monitoring at the Buck Island Bar (BAR) and South Fore Reef (SFR). The bleaching threshold of 29.5°C is plotted as a dashed red line.
NPS / SFCN

South Fore Reef

Monitoring at SFR occurred near the thermal minimum for most of the dataset, except for episodic monitoring in November 2005 and October 2010. Figure 21 displays bleaching prevalence (% of observed corals with bleaching) and severity (BL1–BL4) data for South Fore Reef and the Buck Island Bar, as well as the accumulated thermal stress (in degree heating weeks, °C-weeks) of water temperatures that led to the observed bleaching response. There have been four instances where coral bleaching prevalence and severity spiked in response to thermal stress over the course of monitoring at South Fore Reef (2002–2024):

1. The most intense response occurred during episodic monitoring in November 2005 when 95.9% of all observed corals bleached to some extent and 58.8% of those exhibited severe bleaching (BL1). By the time annual monitoring occurred in March 2006, 75.6% of corals bleached to some extent with 13.8% of those being severe.
2. Episodic monitoring in October 2010 showed that 30.4% of corals exhibited bleaching, with 3.5% showing severe signs. This receded to 25.2% of corals that exhibited bleaching with 0% showing severe signs by the time annual monitoring occurred in February 2011.
3. In February 2020, 33.8% of corals appeared bleached, with 5.0% of those showing severe signs. The next year, in February 2021, only 4.5% of corals were bleached with 0.0% showing severe signs.
4. In April 2024, 35.7% of corals were bleached with 0.0% of those corals showing severe signs.

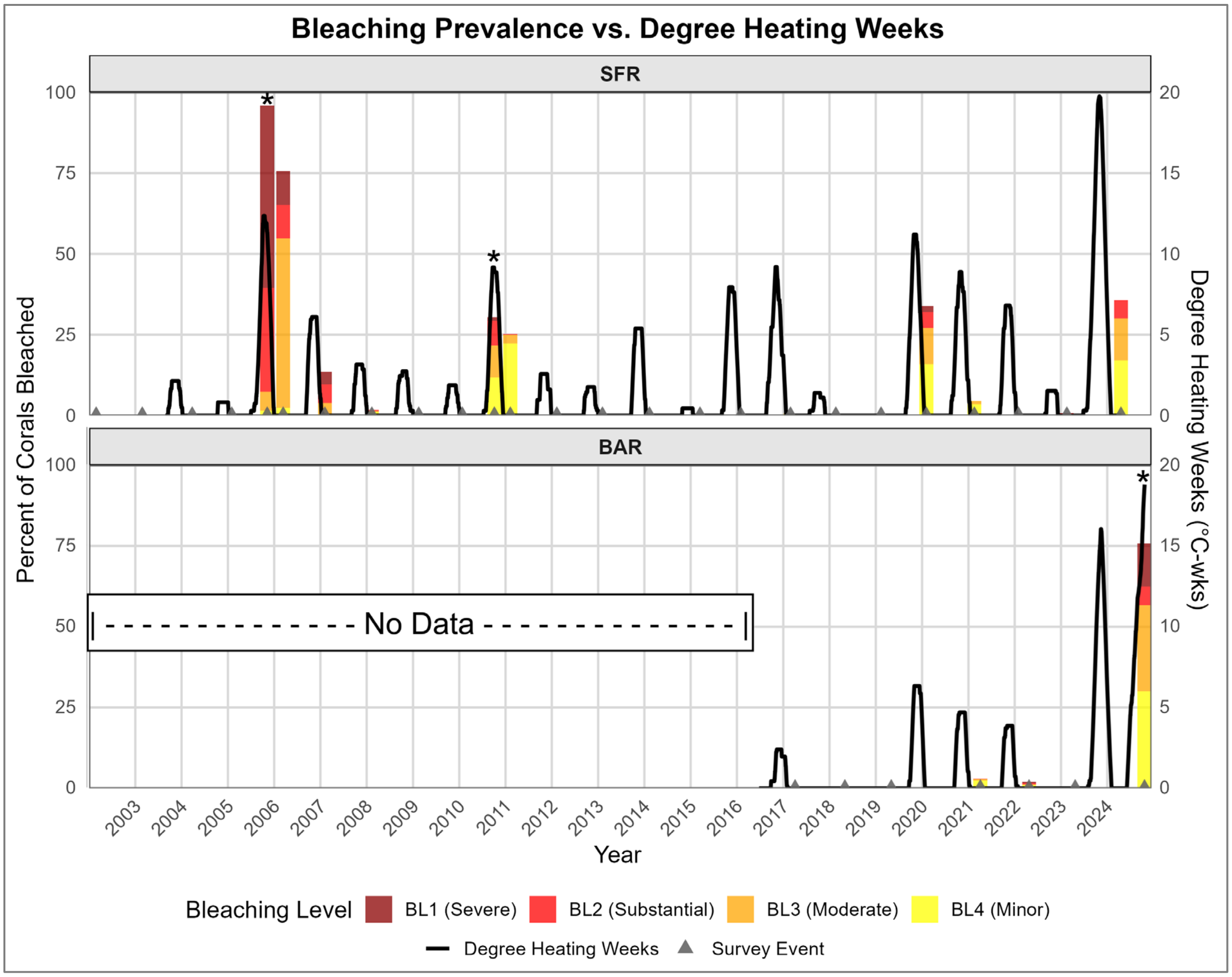

Figure 21. A comparison of bleaching response and accumulated thermal stress. Bleaching response is plotted along the primary Y axis in a stacked bar plot indicating prevalence and severity of bleached corals from video monitoring at South Fore Reef (SFR) and Buck Island Bar (BAR) monitoring sites. Bleached corals are categorized as BL1 (Severe, dark red), BL2 (Substantial, red), BL3 (Moderate, orange), and BL4 (Minor, yellow). Monitoring typically occurred near the seasonal thermal minimum, except for events denoted with a star (*) that indicate monitoring that occurred near the thermal maximum, which could result in a more pronounced observed bleaching response. Accumulated thermal stress is plotted as degree heating weeks (°C-weeks) on the secondary Y axis (black line) from water temperature data recorded continuously every 2 hours at reef depth at SFR and BAR. There is no temperature data from SFR from 2003 to 2005 and the values from a nearby site, Western Spur and Groove, are plotted as a proxy.
NPS / SFCN

Buck Island Bar

Monitoring at the BAR occurred near the thermal minimum for most of the dataset, except for annual monitoring in 2024, which took place in October. At the BAR there was only one instance where bleaching prevalence and severity spiked in response to thermal stress over the duration of monitoring from 2017 to 2024 (Figure 21):

1. In October 2024, 75.8% of corals showed signs of bleaching, with 17.6% of bleached corals exhibiting severe signs (BL1).

Discussion

Stony Coral Cover

Long-term changes in stony coral cover at South Fore Reef (SFR) and Buck Island Bar (BAR) reflect periods of gradual growth and stability during intervals without severe disturbances, punctuated by rapid declines associated with episodic severe disturbance events. Across both sites, the most substantial declines in coral cover were associated with severe bleaching and disease outbreaks, while moderate bleaching events and major hurricanes produced comparatively limited measurable change.

The most significant early decline occurred at SFR following the 2005 bleaching event and subsequent White Plague outbreak, which resulted in an 80% loss of coral cover (Miller et al. 2009). While the link between thermal stress and disease can vary, the increased thermal stress in 2005 may have contributed to the outbreak of White Plague that occurred soon after (Brandt and McManus 2009; Eakin et al. 2010; Miller et al. 2009; Randall et al. 2014). White Plague affects several stony coral species (Cróquer et al. 2021; Weil et al. 2006), and *Orbicella* spp., the dominant corals at South Fore Reef, suffered the greatest losses.

In the absence of major disturbances, coral cover at SFR increased steadily from 2007 to 2021, representing one of the strongest recovery periods observed among SFCN monitoring sites in the U.S. Virgin Islands (SFCN 2024a, 2024b, 2024c). This recovery was largely driven by the regrowth of dominant genera, *Orbicella* and *Porites*, and coincided with a period of relatively low disease prevalence.

In contrast, more moderate thermal stress events (e.g., 2010 and 2019) and the 2017 hurricanes did not correspond with measurable declines in coral cover at either site. While bleaching responses were observed during moderate thermal events, the absence of associated disease outbreaks and lower overall thermal stress likely limited coral mortality. Additionally, the corals and/or their algal symbiont communities that survived more intense prior bleaching events (e.g., 2005) may have increased tolerance to thermal stress (Cunning and Baker 2020; DeMerlis et al. 2022; Fifer et al. 2026; Parker et al. 2020).

Similarly, despite their intensity, Hurricanes Irma and Maria did not produce clear declines in coral cover at the monitored depths. While considerable physical damage was documented in shallow reef habitats, the depths of South Fore Reef (40–50 feet [12.2–15.2 m]) and Buck Island Bar (100–130 feet [30.5–39.6 m]) likely provided a degree of protection from wave energy, reducing storm-related impacts (Storlazzi et al. 2021; Viehman et al. 2020). Weaker storms or near-misses can introduce cooler water to reefs near their thermal peak and provide relief from bleaching stress (Carrigan and Puotinen 2014; Manzello et al. 2007b).

Elevated prevalence of White Plague at the BAR contributed to a gradual decline in coral cover from 2017–2019, in contrast to SFR where disease prevalence remained low and coral cover stable. This difference is likely related to higher coral cover and host density at BAR, which can facilitate greater disease transmission and prolonged outbreak conditions (Aeby et al. 2011; Myers and Raymundo 2009). A similar pattern emerged during the outbreak of Stony Coral Tissue Loss Disease (SCTLD). After the first documented observation of SCTLD within Buck Island Reef NM in January 2021 and the rapid spread thereafter (VICDAC 2025), coral cover declined rapidly at both SFR and BAR, with greater losses observed at BAR (Figure 22). Species-specific susceptibility further influenced outcomes, with highly susceptible taxa experiencing substantial declines while less susceptible genera (e.g., *Porites* and *Agaricia*) persisted or increased in relative abundance (Brandt et al. 2021; Meiling et al. 2021; Papke et al. 2024). The moderately-susceptible *Orbicella*, the clear dominant genus at SFR, now shares nearly identical percent coverage (2.3% vs. 2.0%) with the *Porites* genus, marking what could be an ecological shift.

Figure 22. This image shows a colony of *Orbicella annularis* (top) and *Pseudodiploria strigosa* (bottom) with multiple disease lesions during the Stony Coral Tissue Loss Disease outbreak. Healthy coral tissue is dark tan in color, where disease lesions with recent mortality are stark white.
NPS / LEE RICHTER

Following the SCTLD outbreak, severe thermal stress in 2023 and 2024 contributed to additional coral loss (Figure 23). At SFR, declines observed in 2024 are consistent with delayed mortality following the 2023 bleaching event. At BAR, the magnitude of drivers of recent declines are less clear but likely reflect a combination of residual disease effects and bleaching-related mortality. The timing of monitoring relative to peak thermal stress means additional bleaching-related mortality is expected at both sites following the 2024 severe bleaching event. Different species have variable responses to thermal stress and while bleached corals can recover, prolonged thermal stress can lead to pronounced mortality of heat-susceptible corals like *Millepora* spp. and *Agaricia agaricites* (Levas et al. 2018; Smith et al. 2013).

Figure 23. This image shows a colony of *Orbicella annularis* undergoing bleaching from thermal stress in 2023. Different parts of the same colony may exhibit different severity of bleaching. The most severe bleaching (BL1) is pure white, while minor bleaching (BL4) is only slightly discolored. The only normal, unbleached tissue in the image is the dark tan area in the low section in the middle of the colony.
NPS / LEE RICHTER

Differences in thermal regime between sites likely influence bleaching responses. The deeper BAR site typically experiences lower temperatures than the shallower SFR site, which may buffer it from moderate thermal stress (Goodbody-Gringley and Chequer 2025). However, mesophotic corals may have lower thermal tolerance, and during the extreme heat events of 2023–2024, elevated temperatures reached deeper depths and exceeded previous maxima (Smith et al. 2016). This suggests while depth may provide protection during moderate events, it may increase vulnerability during severe thermal stress, potentially contributing to greater recent declines at BAR.

Overall, trends at both sites indicate stony coral cover trajectories are shaped by episodic severe disturbance events (Figures 24 and 25). Periods without major disturbances allow for gradual recovery (e.g., SFR), while successive disturbances, especially disease outbreaks and thermal stress, can result in rapid and sustained declines. In contrast, moderate thermal stress (<12 DHW) did not appear to drive substantial coral mortality at these sites. Although bleaching responses were observed during these events, most corals survived and may have acclimatized to elevated temperatures, potentially increasing tolerance to subsequent thermal stress (Berkelmans and van Oppen 2006; Fifer et al. 2026; Levas et al. 2018; Logan et al. 2013). Differences between sites suggest that depth, coral community composition, and host density influence both the magnitude and duration of disturbance impacts.

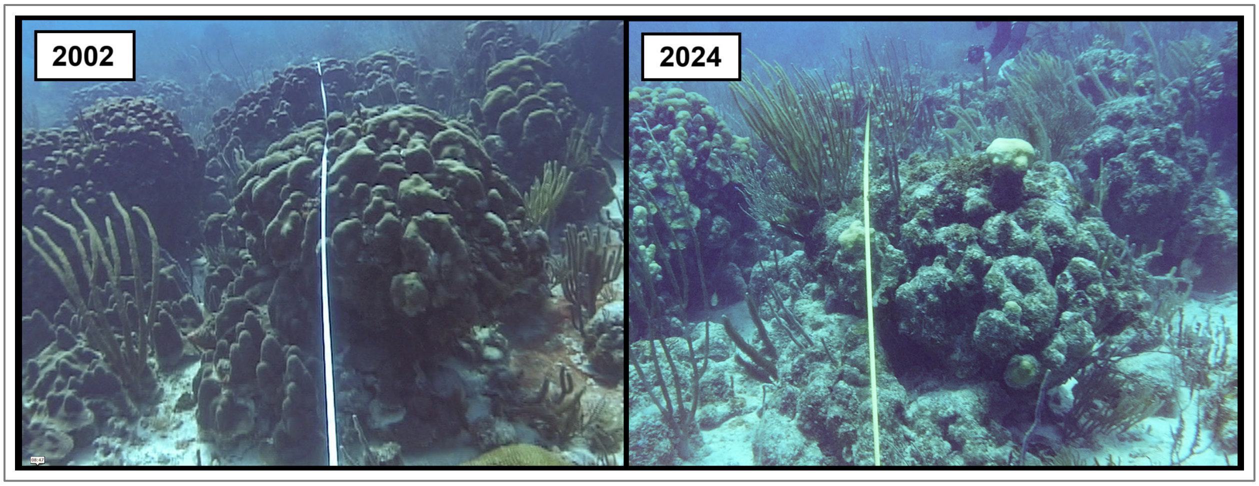

Figure 24. These two images were captured from initial video monitoring in 2002 (left) and the most recent monitoring in 2024 (right) on Transect 12 at South Fore Reef. The amount of live coral cover declined considerably over the timeframe, though physical carbonate structures remain in a degraded form.
NPS / SFCN

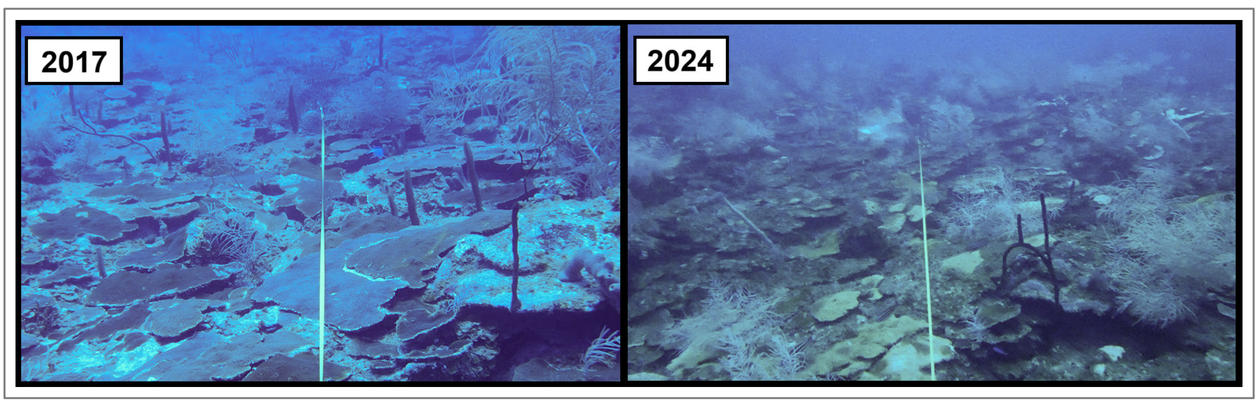

Figure 25. These two images were captured from initial video monitoring in 2017 (left) and the most recent monitoring in 2024 (right) on Transect 2 at Buck Island Bar—BAR02. The amount of live coral cover declined considerably over the timeframe, though physical carbonate structures remain in a degraded form.
NPS / SFCN

Gorgonian Cover

In contrast to stony corals, gorgonian cover remained relatively stable at South Fore Reef and Buck Island Bar over the duration of monitoring. Cover fluctuated within a narrow range at both sites, with no clear long-term directional trends.

This stability likely reflects fundamental biological differences between gorgonians and stony corals. Gorgonians are affected by a different suite of pathogens (Kim 2016; Weil et al. 2016) and generally exhibit greater tolerance to thermal stress (Goulet et al. 2017; Lasker 2005; Lasker et al. 2020), which may contribute to their relative resistance to disturbance-driven declines. However, interpretation is limited by available data, as species-level composition and metrics such as bleaching and disease are not recorded for gorgonians, resulting in a less detailed understanding of their population dynamics compared to stony corals.

Changes in gorgonian cover did not consistently correspond with known disturbance events. A decline at SFR between 2022 and 2024 may be associated with recent thermal stress, though a similar response was not observed at BAR, and the magnitude of change remains within the range of historical variability. Additional monitoring is needed to determine whether recent fluctuations represent a legitimate response to disturbance or natural variability.

Stony Coral Species Richness

Trends in stony coral species richness at SFR and BAR closely mirror changes observed in coral cover, with declines primarily associated with disturbance events. The most pronounced reductions in species richness occurred following the SCTLD outbreak, which resulted in the loss of multiple susceptible species across both sites.

Declines in richness were largely driven by the loss of less common, but ecologically distinct, species rather than dominant reef-builders. While major genera such as *Orbicella*, *Porites*, and *Agaricia* experienced changes in cover, their continued presence on transects meant overall richness was more strongly influenced by the disappearance of rarer, highly susceptible taxa, especially those in the Meandrinidae family (Beavers et al. 2023; Brandt et al. 2021; Meiling et al. 2021; SCTLD Case Definition 2018). This highlights the disproportionate role disease can play in reducing biodiversity, even when dominant species persist.

Differences in the timing and magnitude of richness declines between sites likely reflect variation in community composition and species susceptibility. SFR experienced earlier declines following SCTLD, potentially due to a greater proportion of highly susceptible species, whereas BAR exhibited a more gradual reduction in richness. These differences are consistent with site-level variation in host composition and disease dynamics.

Limited evidence suggests some species may be reappearing following the decline in SCTLD prevalence, though recovery remains uncertain and appears to be site-specific. However, recent thermal stress events in 2023 and 2024 likely contributed to additional, albeit smaller, reductions in richness, particularly among thermally sensitive taxa in the Agaricidae and Milleporidae families (Smith et al. 2013). For example, a decline in species richness was observed at SFR during the 2010 moderate bleaching event, followed by a period of stability and gradual recovery. This response likely reflects the loss of thermally sensitive species during that event. Yet, a comparable moderate bleaching event in 2019 did not produce a detectable change in richness, suggesting extant corals may have increased their tolerance to moderate thermal stress over time (Fifer et al. 2026).

A small number of coral species (e.g., *Madracis decactis, Stephanocoenia intersepta*, *Porites astreoides*) appear to have remained stable or increased in occurrence over time, suggesting some degree of resilience to disease and thermal stress (Charpentier 2014; Wallace et al. 2025). These taxa may be less susceptible to disturbance or better able to persist under changing environmental conditions. However, these trends should be interpreted cautiously, as changes in detectability, particularly following declines in dominant reef-building corals, can influence observed trends (MacKenzie et al. 2002).

These findings indicate long-term declines in species richness at both sites are driven primarily by disease outbreaks, with thermal stress acting as a secondary driver. The 2017 hurricanes did not result in lasting changes to species richness. Although short-term fluctuations were observed, richness soon returned to pre-hurricane levels, suggesting limited impacts at the monitored depths. While some variability may reflect differences in detection among surveys, the loss of susceptible species following major disturbances indicates a shift in reef composition toward a reduced and less functionally diverse coral community.

Synthesis & Management Implications

Collectively, reef trajectories in Buck Island Reef National Monument appear to be governed less by gradual environmental change and more by the interaction between disturbance intensity and community susceptibility, consistent with Caribbean reef studies demonstrating that episodic disturbances drive shifts in community structure through selective loss or gain of susceptible taxa rather than uniform change (Cramer et al. 2021; Cresswell et al. 2023; Hughes 1994). While this report focuses on the effects of disturbance events on reef communities, other chronic stressors—including degraded water quality, nutrient enrichment, sedimentation, and macroalgal competition—may also influence coral condition and resilience (Oliver et al. 2018; Szmant 2002). These factors were not evaluated in the present study but may interact with thermal stress and disease to affect long-term reef condition and recovery.

Managing for the impacts of large-scale disturbances such as marine heat waves, hurricanes, and coral disease outbreaks is challenging and not feasible in some cases. Once established, disease outbreaks are difficult to contain; prioritizing prevention is often more effective than response. For this reason, management efforts are most impactful when they focus on reducing local stressors that compound reef vulnerability. Regulating appropriate boating practices and promoting responsible snorkeling and diving can help minimize direct human impacts. By alleviating these local pressures, reefs are afforded the opportunity to recover and grow, thereby enhancing their resilience to broader regional and global stressors.

In addition to reducing local stressors, active restoration has emerged as an important management tool in the Caribbean. Restoration efforts, including coral propagation and outplanting, are being used to enhance population recovery, particularly for highly susceptible and ecologically important reef-building species (NOAA 2020). While restoration is unlikely to offset losses from large-scale disturbances at the ecosystem level, it can support localized recovery, maintain genetic diversity, and preserve key species that contribute disproportionately to reef structure and function (VI-RoCS 2023). When combined with efforts to reduce local stressors, restoration may help stabilize reef communities and enhance their capacity for recovery following disturbance.

Summary

Severe disturbance events have been the primary drivers of change in reef composition at coral monitoring sites in Buck Island Reef National Monument. Disease outbreaks and severe bleaching events produced the most substantial declines in stony coral cover and species richness, while moderate bleaching events and hurricanes had comparatively limited and short-lived effects at monitored depths. The recent Stony Coral Tissue Loss Disease outbreak appears to have waned, but the full impacts of the extreme thermal stress observed in 2023–2024 remain uncertain and will require continued monitoring.

In contrast to stony corals, gorgonian cover remained relatively stable over the course of monitoring, reflecting differences in susceptibility to disease and thermal stress. This stability highlights divergent responses among major benthic groups under similar disturbance regimes.

Despite substantial losses during disturbance events, the stony coral community at South Fore Reef demonstrated the capacity for recovery during periods without major disturbance, particularly from 2007 to 2021. Corals and/or their algal symbiont communities may have acclimatized to changing environmental conditions, potentially increasing their tolerance to moderate thermal stress. However, long-term trends suggest an ongoing shift in community composition, with declines in historically dominant reef-building corals such as *Orbicella* and increasing relative abundance of more disturbance-tolerant taxa such as *Porites*. These trends are consistent with a transition toward a less structurally complex and less functionally diverse reef community.

Long-term declines in coral cover and species richness at these sites are consistent with past disturbance-driven observations documented in Buck Island Reef NM (Bythell et al. 2000; Gladfelter et al. 1977; Rogers 2022; Rogers et al. 2003). Loss of live coral reduces reef structural complexity and can accelerate carbonate erosion, with potential consequences for reef-associated organisms that depend on complex habitat structure (Coker et al. 2014; Graham and Nash 2013; Komyakova et al. 2013; Medellín-Maldonado et al. 2023).

Although South Fore Reef and Buck Island Bar were influenced by the same major disturbances, their responses differed in magnitude and trajectory. South Fore Reef exhibited periods of recovery in the absence of disease, whereas Buck Island Bar experienced more sustained declines, likely associated with higher coral cover and host density that amplified disease impacts. More recent thermal stress events contributed to additional losses at both sites, with depth-related differences in thermal exposure and tolerance potentially influencing site-specific responses. Collectively, while disturbance events drive change across the monument, local factors such as depth, host composition, and community structure shape how each reef responds, resulting in distinct but related ecological trajectories.

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Appendix A. Coral Species, Disease, and Bleaching Codes

Table 2 lists the four-letter codes used to identify coral species, while Table 3 lists the codes used to identify coral diseases and bleaching levels.

For species richness calculations, some coral species are grouped together to reduce observer effects from common identification errors:

- All *Orbicella* species are grouped together as ORBI.
- *Porites porites, P. divaricata*, and *P. furcata* are grouped together as PPOR.
- All *Scolymia* species are grouped as SCOL.

Table 2. Coral species codes.

Species Category	Species Name	Code
General Coral Species	*Acropora cervicornis*	ACER
	Acropora palmata	APAL
	Acropora prolifera	APRO
	Agaricia spp.	AGAR
	Agaricia fragilis	AFRA
	Agaricia grahamae	AGRA
	Agaricia lamarcki	ALAM
	Agaricia undata	AUND
	Colpophyllia natans	CNAT
	Dendrogyra cylindrus	DCYL
	Dichocoenia stokesii	DSTO
	Diploria labyrinthiformis	DLAB
	Eusmilia fastigiata	EFAS
	Favia fragum	FFRA
	Helioseris cucullata	HCUC
	Isophyllia rigida	IRIG
	Isophyllia sinuosa	ISIN
	Madracis spp.	MADR
	Madracis aurentenra	MAUR
	Madracis decactis	MDEC
	Madracis formosa	MFOR
	Madracis pharensis	MPHA
	Madracis senaria	MSEN
	Manicina areolata	MARE
	Meandrina jacksoni	MJAC

Table 2 (continued). Coral species codes.

Species Category	Species Name	Code
General Coral Species (cont.)	*Meandrina meandrites*	MMEA
	Montastraea cavernosa	MCAV
	Mussa angulosa	MANG
	Mycetophyllia spp.	MYCE
	Mycetophyllia aliciae	MALI
	Mycetophyllia danaana	MDAN
	Mycetophyllia ferox	MFER
	Mycetophyllia lamarckiana	MLAM
	Oculina diffusa	ODIF
	Orbicella spp.	ORBI
	Orbicella annularis	OANN
	Orbicella faveolata	OFAV
	Orbicella franksi	OFRA
	Porites astreoides	PAST
	Porites branching spp.	PORI
	Porites branneri	PBRA
	Porites divaricata	PDIV
	Porites furcata	PURF
	Porites porites	PPOR
	Pseudodiploria spp.	PSEU
	Pseudodiploria clivosa	PCLI
	Pseudodiploria strigosa	PSTR
	Scolymia spp.	SCOL
	Scolymia cubensis	SCUB
	Scolymia lacera	SLAC
	Siderastrea spp.	SIDE
	Siderastrea radians	SRAD
	Siderastrea siderea	SSID
	Solenastrea spp.	SOLE
	Solenastrea bournoni	SBOU
	Solenastrea hyades	SHYA
	Stephanocoenia intersepta	SINT
	Tubastraea aurea	TAUR
	Undaria spp.	UNDA
	Undaria agaricites	UAGA
	Undaria humilis	UHUM
	Undaria tenuifolia	UTEN

Table 2 (continued). Coral species codes.

Species Category	Species Name	Code
Other Coral Codes	*Antipatharia* (Black coral)	ANTI
	Millepora spp.	MILL
	Millepora alcicornis	MALC
	Millepora complanata	MCOM
	Millepora squarrosa	MSQU
	Stylaster roseus	SROS

Table 3. Coral disease and bleaching codes.

Category	Name	Code
Coral Diseases	Black band disease	BB
	Stony Coral Tissue Loss Disease	SCTLD
	White band disease	WB
	White Blotch	WBLO
	White Plague	WPL
	White Pox	WPX
	Yellow Band	YB
	Dark Spot	DS
	Dark Spot: Type 1	DS1
	Dark Spot: Type 2	DS2
	Dark Spot: Type 4	DS4
Coral Bleaching	Bleaching Level 1	BL1
	Bleaching Level 2	BL2
	Bleaching Level 3	BL3
	Bleaching Level 4	BL4

Appendix B. Accessible Tables

Tables 4 and 5 contain tabular data from figures found in the main body of the report.

Table 4. Data from Figure 15. The percentage of transects at South Fore Reef where stony coral species were present (total transects = 20). NP indicates that a species was not present. Species are grouped into categories based on what they are susceptible to (Suscep. To); in this column, SCTLD stands for Stony Coral Tissue Loss Disease. The full list of species codes is available in Appendix A. Disturbances include moderate bleaching events that occurred in 2010 and 2019, severe bleaching events that occurred in 2023 and 2024, hurricanes that occurred in 2017, and disease outbreaks that occurred in 2021.

Suscep. To	Species	2010-Jan	2010-Oct	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
SCTLD (High)	PSTR	90%	65%	70%	90%	90%	95%	95%	95%	90%	90%	95%	95%	100%	95%	85%	80%
	CNAT	80%	80%	70%	80%	80%	85%	90%	80%	85%	85%	70%	75%	75%	50%	30%	25%
	MMEA	80%	60%	80%	65%	60%	75%	70%	75%	80%	60%	75%	75%	75%	NP	NP	5%
	EFAS	80%	80%	65%	75%	80%	70%	80%	65%	70%	40%	55%	60%	50%	5%	NP	10%
	DLAB	65%	55%	45%	35%	45%	50%	55%	50%	55%	35%	55%	50%	50%	25%	10%	10%
	DSTO	70%	35%	40%	40%	45%	50%	35%	40%	35%	25%	35%	25%	30%	NP	NP	5%
	DCYL	5%	NP	NP	NP	NP	NP	5%	NP	NP	NP	NP	NP	NP	NP	NP	NP
SCTLD (Medium)	ORBI	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	SSID	95%	80%	90%	85%	95%	90%	95%	95%	95%	80%	100%	100%	100%	95%	95%	100%
	SINT	95%	55%	70%	70%	60%	80%	85%	75%	80%	70%	90%	85%	90%	95%	85%	100%
	MCAV	95%	90%	85%	95%	90%	80%	100%	80%	75%	70%	75%	75%	85%	50%	35%	45%
Heat Sensitive	UAGA	90%	100%	100%	100%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	MALC	100%	70%	85%	95%	100%	100%	100%	95%	100%	95%	100%	100%	100%	100%	95%	100%
	HCUC	45%	NP	15%	25%	20%	20%	50%	30%	40%	5%	45%	20%	45%	45%	35%	15%
	AFRA	NP	NP	NP	65%	35%	NP	15%	NP	5%	50%	35%	45%	45%	10%	45%	NP
NA	PAST	100%	100%	100%	100%	100%	100%	95%	100%	95%	100%	100%	100%	100%	100%	100%	100%
	PPOR	100%	95%	100%	95%	95%	95%	90%	100%	95%	100%	100%	100%	100%	100%	100%	100%
	SCOL	75%	30%	20%	40%	30%	40%	20%	30%	15%	5%	20%	10%	20%	20%	15%	30%
	SRAD	35%	5%	30%	25%	20%	25%	15%	25%	10%	5%	5%	15%	NP	10%	50%	30%

Table 4 (continued). Data from Figure 15. The percentage of transects at South Fore Reef where stony coral species were present (total transects = 20). NP indicates that a species was not present. Species are grouped into categories based on what they are susceptible to (Suscep. To); in this column, SCTLD stands for Stony Coral Tissue Loss Disease. The full list of species codes is available in Appendix A. Disturbances include moderate bleaching events that occurred in 2010 and 2019, severe bleaching events that occurred in 2023 and 2024, hurricanes that occurred in 2017, and disease outbreaks that occurred in 2021.

Suscep. To	Species	2010-Jan	2010-Oct	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
NA (cont.)	MYCE	10%	NP	5%	15%	20%	30%	15%	15%	20%	10%	15%	10%	10%	10%	10%	5%
	MDEC	15%	NP	10%	15%	5%	10%	15%	10%	10%	10%	15%	10%	20%	15%	5%	20%
	ISOP	10%	20%	10%	20%	5%	5%	5%	5%	5%	10%	5%	5%	NP	NP	NP	NP
	MANG	25%	5%	5%	5%	10%	5%	5%	NP	NP	NP	NP	NP	NP	NP	NP	NP
	FFRA	20%	15%	5%	NP	NP	5%	NP	NP	NP	5%	NP	5%	NP	NP	NP	NP
	ALAM	NP	NP	NP	NP	NP	NP	NP	NP	NP	5%	10%	10%	5%	NP	NP	NP
	MAUR	NP	5%	5%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
	MARE	NP	NP	NP	10%	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
	ACER	NP	NP	NP	NP	NP	NP	NP	NP	NP	5%	NP	NP	NP	NP	NP	NP
	APAL	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	5%	NP	NP	NP	NP

Table 5. Data from Figure 17. The percentage of transects at Buck Island Bar where stony coral species were present (total transects = 16). NP indicates that a species was not present. Species are grouped into categories based on what they are susceptible to (Suscep. To); in this column, SCTLD stands for Stony Coral Tissue Loss Disease. The full list of species codes is available in Appendix A. Disturbances include a moderate bleaching event that occurred in 2019, severe bleaching events that occurred in 2023 and 2024, hurricanes that occurred in 2017, and disease outbreaks that occurred in 2021.

Suscep. To	Species	2017	2018	2019	2021	2022	2023	2024
SCTLD (High)	CNAT	56%	44%	38%	38%	31%	12%	12%
	MMEA	38%	38%	38%	19%	NP	NP	NP
	PSTR	19%	25%	6%	19%	6%	NP	NP
	EFAS	6%	6%	12%	6%	NP	NP	NP
	DSTO	6%	NP	NP	NP	NP	NP	NP
SCTLD (Medium)	ORBI	100%	100%	100%	100%	100%	100%	100%
	MCAV	100%	100%	100%	100%	88%	50%	50%
	SINT	81%	94%	81%	75%	94%	75%	88%
	SSID	75%	88%	94%	69%	69%	62%	88%
Heat Sensitive	MALC	88%	100%	94%	100%	100%	94%	81%
	UAGA	94%	88%	88%	100%	100%	100%	88%
	HCUC	31%	38%	44%	38%	56%	44%	NP
	AFRA	31%	NP	25%	6%	19%	25%	12%
NA	ALAM	100%	100%	100%	88%	100%	100%	100%
	PAST	94%	100%	100%	94%	100%	100%	100%
	MDEC	50%	62%	62%	81%	81%	88%	88%
	PPOR	56%	69%	50%	69%	88%	69%	81%
	MYCE	44%	12%	25%	19%	12%	6%	NP
	SROS	NP	NP	NP	NP	6%	19%	6%
	SCOL	NP	NP	NP	6%	6%	6%	6%
	MANG	NP	6%	NP	NP	NP	6%	6%
	SRAD	NP	NP	6%	NP	NP	NP	NP

National Park Service
U.S. Department of the Interior

Science Report NPS/SR—2026/459
https://doi.org/10.36967/2318409

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

NPS 163/199750, July 2026