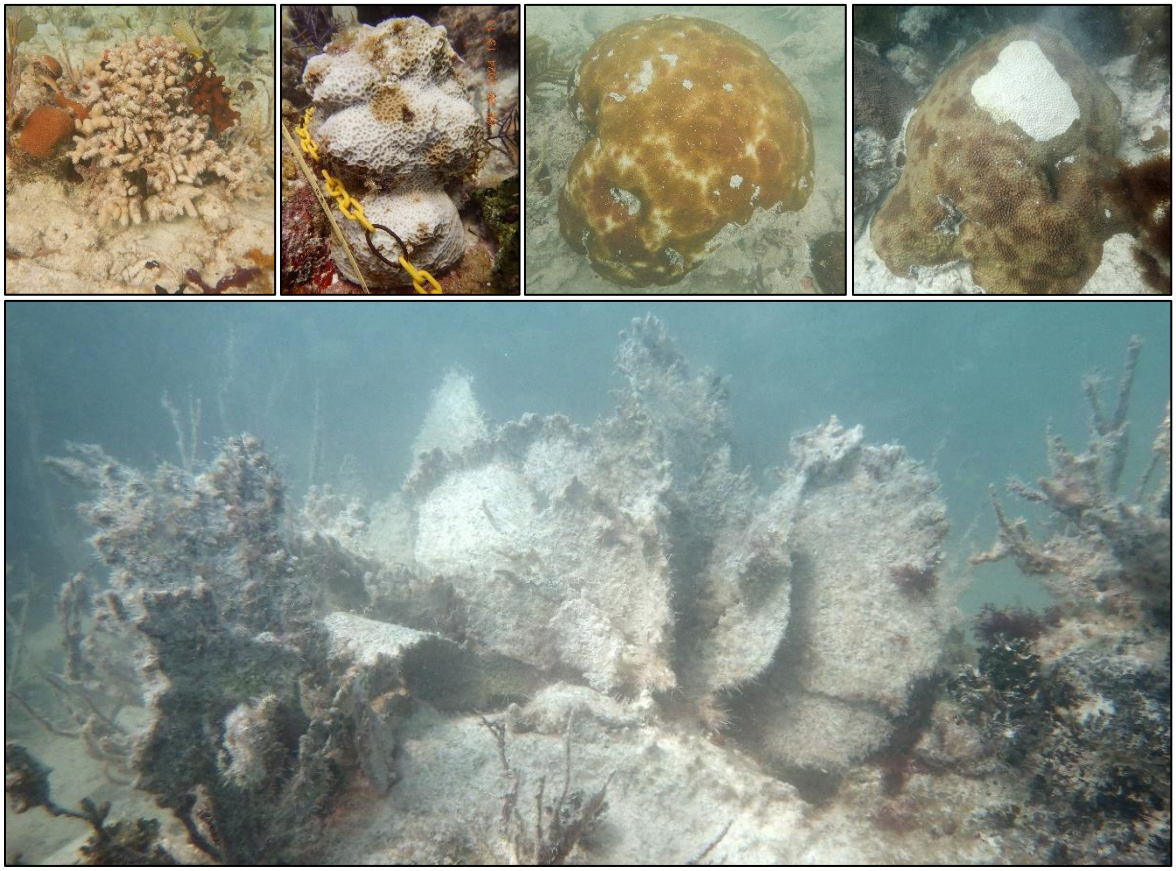
Florida's Coral Reef 2023-2024 Post-Bleaching Assessment Quick Look Report



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This report presents data from post-bleaching surveys conducted between January 15th and March 31st, 2024. *The content and opinions expressed herein are those of the author(s) and do not necessarily reflect the position or the policy of NOAA or The Nature Conservancy, and no official endorsement should be inferred.*

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https://ocean.floridamarine.org/FRRP/Home/About
https://myfwc.com/research/habitat/coral/

Cover page photographs: Upper left to right: pale *Porites porites* colony with old mortality, partially bleached *Agaricia agaricites*, partially bleached *Siderastrea siderea*, and pale *Montastraea cavernosa*. Bottom: dead sea fans (*Gorgonia ventalina*) and dead sea rods. All images were collected during the 2024 winter post-bleaching surveys.

INTRODUCTION

Created and first implemented by the former Florida Reef Resilience Program (FRRP), the Disturbance Response Monitoring (DRM) program was developed to annually assess coral condition during the months of peak thermal stress along Florida's Coral Reef (FCR). The 2005 severe coral bleaching event in the Florida Keys prompted the establishment of the DRM program, which has continued to implement these surveys every year. DRM is a collaborative effort among local, state, and federal environmental managers, scientists, conservation organizations, and coral restoration practitioners, all of whom are driven by a common goal of providing valuable and timely coral condition data to all reef stakeholders. The primary objectives of the DRM program have always been to provide a condition report on the annual status of bleaching along the reef tract. This information is used to identify resilient areas of the reef, promote appropriate management or conservation strategies for reef areas based on resilience, and aid management in research and restoration decisions.

The Coral Reef Evaluation and Monitoring Project (CREMP) started annual monitoring at permanently established reef sites in the Florida Keys in 1996, the Dry Tortugas in 1999, and in Southeast Florida (SECREMP) in 2003. It is a repeated measures program which provides information on the temporal trends of corals and benthic percent cover. In 2011, demographic surveys of corals and octocorals were added to the CREMP experimental design to provide a more robust measure of population abundance and colony condition. While stony corals build the physical framework of the reef, octocorals are among the most abundant benthic fauna in some reef habitats, providing important canopy habitat for fish and other reef organisms. Benthic water temperature is also monitored at all CREMP sites to help correlate changes in the benthic community with fluctuations in water temperatures. Together, CREMP, conducted by the Florida Fish and Wildlife Research Institute (FWRI), and SECREMP, conducted by Nova Southeastern University (NSU), have been instrumental in understanding reef change and the effect of management actions on FCR.

If the DRM program records severe coral bleaching during the annual summer assessment, it will implement post-bleaching surveys three to four months after the summer bleaching event. After the 2005, 2014, and 2015 bleaching events, the DRM program conducted post-bleaching surveys targeting areas where >50% of the entire surveyed population was fully or partially bleached. The CREMP programs provide especially useful monitoring sites at which to conduct post-bleaching surveys locally or regionally across FCR because comparisons to the previous year's data from the permanent transects allow for precise measurements of change in coral populations.

The 2023 DRM surveys recorded the worst bleaching event in the history of the program, despite milder conditions experienced by the northern portion of FCR (2023 DRM Summer Quick Look Report). According to NOAA's Coral Reef Watch, sea surface temperatures above 30.5° C - the coral bleaching threshold - began in mid-June and remained elevated through August, often above the coral mortality threshold of 32.0° C, and spiked again in mid-September. This resulted in a

prolonged bleaching period of dangerously high temperatures throughout the summer. Pooled by habitat zone within each subregion of FCR, corals in 19 of the 32 subregion-zones surveyed in 2023 were severely bleached (>50% prevalence), including every zone between Biscayne and the Dry Tortugas, except for one zone in the Marquesas. In addition, a high prevalence of octocoral mortality from thermal stress was observed throughout the Florida Keys and Dry Tortugas.

The combination of severe bleaching and coral mortality prompted the DRM program to conduct post-bleaching coral surveys and the CREMP program to conduct its first-ever post-bleaching surveys of octocorals. A subset of CREMP sites in the Upper, Middle, and Lower Keys subregions were selected for post-bleaching coral and octocoral surveys. Because no subregion-zones in Southeast Florida surpassed bleaching thresholds, no SECREMP sites were selected for post-bleaching surveys. Additionally, because bleaching conditions began in early July 2023, partner teams prepared a subset of summer DRM sites from the Biscayne, Upper Keys, Middle Keys, and Lower Keys subregions for post-bleaching coral surveys by installing temporary markers in the reef, to create additional repeated measures survey sites. This increased the total sample size for the post-bleaching coral assessment and filled in spatial gaps between the selected CREMP sites.

This report 1) summarizes summer 2023 water temperature data from CREMP sites, 2) describes the differences in mean coral abundance and live tissue area between the DRM and CREMP 2023 summer surveys and the 2024 post-bleaching surveys, and 3) describes the differences in mean octocoral colony counts and the sum of the colony heights of CREMP target octocoral species between the CREMP 2023 summer surveys and the 2024 post-bleaching assessments.

METHODS

Temperature

CREMP bottom-water temperature data were used to demonstrate the severity of the 2023 thermal stress event. Bottom-water temperatures are recorded hourly using HOBO Water Temp Pro V2 (model U22-001; Onset Corporation) data loggers attached to the CREMP permanent transect stakes installed in the substratum. Because CREMP does not have sites in the Biscayne subregion, an additional logger from SECREMP, located at the northern end of Biscayne, was included. SECREMP loggers follow a similar deployment as CREMP loggers, but record temperatures every other hour. Spanning 2011-2023, the number of days from July through October when the mean daily temperature exceeded the critical thresholds of 30.5°C (coral bleaching) and 32.0°C (coral mortality) was calculated for each year at up to 25 sites. To evaluate the differences in thresholds between 2023 and the last major bleaching event in 2015, temperature data from 36 sites were used to compare the number of days above the critical thresholds across subregions and habitats.

DRM post-bleaching coral species criteria

Due to the changing species composition on the reef, the criteria for post-bleaching surveys were revised in 2023 to determine whether post-bleaching assessments were warranted. These criteria focused on areas where severe bleaching occurred on a selection of 16 ecologically important target species, including *Acropora cervicornis, Acropora palmata, Colpophyllia natans, Dichocoenia stokesii, Diploria labyrinthiformis, Meandrina meandrites, Montastraea cavernosa, Mussa angulosa, Mycetophyllia aliciae, Mycetophyllia ferox, Mycetophyllia lamarckiana, Orbicella annularis, Orbicella faveolata, Orbicella franksi, Pseudodiploria clivosa,* and *Pseudodiploria strigosa.*

Post-bleaching surveys were initiated according to the following criteria pooled across the 16 target species at the subregion-zone level: 1) the prevalence of bleached and partially bleached colonies reached or exceeded 50% or 2) the prevalence of bleached, partially bleached, and pale colonies reached or exceeded 75%. Although 16 target coral species were used in selecting sites for post-bleaching surveys, the survey methodology and data analyses included colonies of all coral species ≥4cm in size. The revised post-bleaching criteria and protocol are available on the DRM website.

Site selection

Bleaching prevalence thresholds were exceeded in every subregion-zone from Biscayne through the Dry Tortugas except the mid-channel zone in the Marquesas subregion, which was surveyed in October after temperatures had begun to decrease. Despite bleaching prevalence thresholds being met, post-bleaching surveys were not planned for the Marquesas and Dry Tortugas subregions due to limited capacity to monitor these remote locations. Because prevalence thresholds were not met off Southeast Florida, no post-bleaching surveys were planned north of Biscayne.

All Upper, Middle, and Lower Keys CREMP sites fell within the subregion-zones that met the DRM bleaching thresholds in 2023 (**Figure 1**). CREMP sites were originally established to represent three reef habitat types in the Florida Keys: patch reefs, shallow forereefs, and deep forereefs. To compare the 2023 CREMP coral surveys to the DRM post-bleaching surveys, the DRM reef habitat classification was used. The DRM classification of reef habitat types lumped the CREMP shallow and deep forereefs together and separated CREMP patch reefs into mid-channel patch reefs and offshore patch reefs.

A total of 23 CREMP sites that met the species composition requirements were selected for DRM post-bleaching coral surveys. All CREMP sites in the Florida Keys have four ~22m fixed transects (stations) that are demarcated by permanent steel stakes installed in the reef framework, designated as the offshore and inshore stakes. Post-bleaching surveys were completed at two of the four stations, prioritizing the stations with the most DRM post-bleaching target species represented

within the 2023 CREMP survey data (**Figure 1**, **Appendix I**). The post-bleaching surveys were conducted along the first 10x1 meters of the CREMP station, beginning at the offshore stake.

At 19 of the 23 CREMP sites selected for coral post-bleaching surveys, CREMP octocoral surveys also were conducted along the first 10x1 meters at two of the four stations, based on the density and diversity of octocorals recorded during the 2023 CREMP surveys. To compare differences in octocorals between the 2023 CREMP surveys and the post-bleaching surveys, the CREMP reef habitat classification was used. The CREMP sites surveyed for octocorals were stratified across the three Keys subregions of Upper, Middle, and Lower Keys and three CREMP habitats of forereef deep, forereef shallow, and patch reef (**Figure 1**, **Appendix I**).

To increase sampling efforts in the DRM subregion-zones where CREMP sites were sparse, additional DRM sites were selected for post-bleaching surveys. Because elevated thermal stress

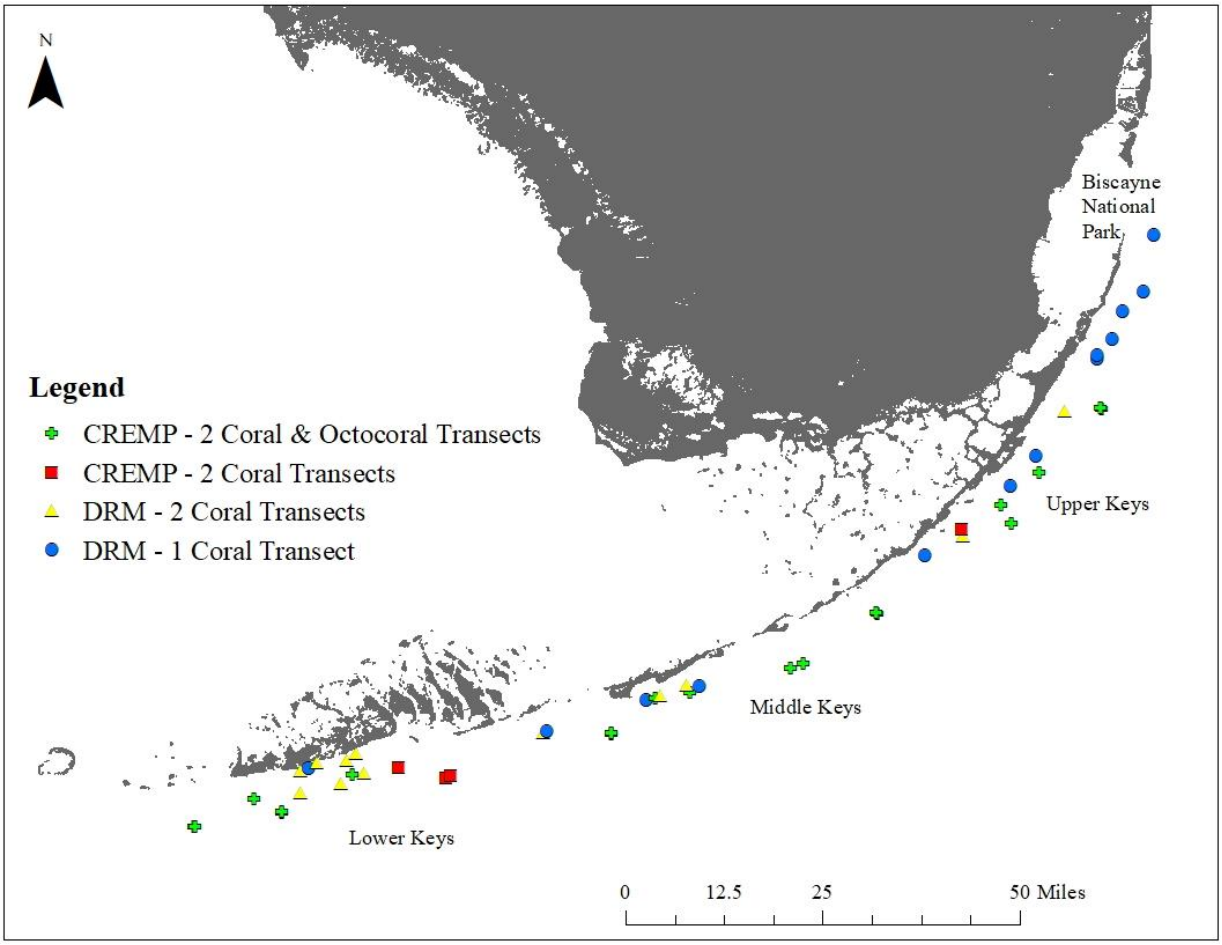

Figure 1. Sites surveyed in 2023 for CREMP or DRM and resurveyed in early 2024 for post-bleaching assessments. Shown are the site types (CREMP and DRM temporary) and the number of transects per site surveyed for corals and octocorals.

began in July 2023, partners were able to prepare a subset of their assigned summer DRM sites that met the species composition requirements from the Biscayne, Upper, Middle, and Lower Keys subregions for post-bleaching surveys in the winter. Temporary masonry nails were inserted into the reef framework at the beginning and end of both of Transects 1 and 2 to ensure the 2023 summer and post-bleaching surveys were performed at the same location. All temporary markers were removed following the post-bleaching survey. In all, 37 DRM sites surveyed during the summer were prepared for post-bleaching surveys.

Due to adverse weather in late fall and early winter, some temporary markers became dislodged and/or visibility was so poor that the exact location of the transect could not be determined during the post-bleaching effort. Therefore, any transect that was missing one or more of its temporary markers was excluded from the post-bleaching analysis. This left 13 of the 37 DRM sites with no transects surveyed and 13 sites with only one transect surveyed. As a result, the comparative analysis between the summer 2023 and 2024 post-bleaching datasets was done at the transect level rather than the site level. This resulted in 81 total transects remaining for analysis from the 60 total sites surveyed (CREMP and DRM sites together; **Appendix I**). The 81 transects were stratified across the four subregions of Biscayne, Upper, Middle, and Lower Keys and the four DRM habitat zones of inshore reef, mid-channel patch reef, offshore patch reef, and forereef (**Figure 1**, **Appendix I**).

Survey methodology

For DRM post-bleaching coral surveys, a metered tape was laid between the two transect markers. Surveyors recorded all stony corals ≥4cm in size with some portion of live tissue within the 10x1m survey transect. Corals were measured for size (maximum diameter and height), assessed for bleaching (whole or partial colony areas of complete color loss), or paling (a precursor to bleaching where coral color is lighter than normal), disease, and percent morality. Percent mortality was assigned as either old mortality, recent mortality due to disease, or recent mortality due to other biotic or abiotic factors. If disease was the cause of recent mortality, surveyors described the rate of tissue loss spread and recorded the recognized disease, if known. For the full DRM methodology, please refer to the DRM in-water survey protocols.

For CREMP octocoral surveys, all arborescent (*i.e.*, non-encrusting) octocorals with any portion of their holdfast found within the 10x1m survey transect were tallied to measure total octocoral abundance. Demographic assessments were conducted for the following target species: *Antillogorgia americana, A. bipinnata, Eunicea flexuosa, Gorgonia ventalina,* and *Pseudoplexaura porosa.* Demographic information included a measurement of maximum colony height, and assessments of structural damage to the colony's axis, the percentage of the axis absent living tissue (*i.e.*, old or recent mortality), and conditions causing recent mortality. For the full methodology, please refer to the CREMP Octocoral Survey SOP.

Data analysis

Temperature data from 25 CREMP sites spread across the Florida Keys subregions and habitats were compared to understand the severity of the 2023 heat stress event in relation to annual thermal stress and previous bleaching years. For each site, the number of days from July 1 through October 30 when the mean daily temperature was above the 30.5°C and 32.0° C critical thresholds was calculated for each year. The records from these 25 sites span from 2011-2023; however, data for some sites were unavailable when the logger either malfunctioned or was not recovered. At minimum, the average for every year in the time series was represented by data from at least 20 sites. The differences in the number of days above a critical threshold across years were analyzed using a Kruskal-Wallis H test and a pairwise Wilcoxin Rank Sum post hoc test in R 4.3.2. Results from the pairwise Wilcoxin Rank Sum post hoc tests were used to group years based upon the likelihood that the mean number of days above a threshold value in a given year was similar (or dissimilar) to other years. Statistical inference was made at $\alpha = 0.05$ and no adjustment for multiple comparisons was made.

Four community metrics were compared to determine differences in the pre- and post-thermal stress coral and octocoral populations. For stony corals, colony abundance and live tissue area (LTA) were analyzed. Colony abundance is the total count of all stony coral colonies ≥4cm in maximum diameter for each transect. Live tissue area was calculated following Walton et al. (2018) in which colony surface area is calculated using the *in situ* colony measurements and Knud Tomsen's approximation for the surface area of an ellipsoid. Then, the estimated partial mortality is subtracted from the total surface area value. The LTA is summed for all colonies of all species for each transect, providing a total LTA value per transect. For octocorals, colony abundance and the total height of all target species were analyzed. Colony abundance equaled the total number of arborescent octocoral colonies of all species for each transect. Total height equaled the sum of all height measurements for the five target species for each transect and is used as an estimate of octocoral biomass.

Changes in these four metrics from summer 2023 to winter 2024 were analyzed using generalized linear mixed models (GLMM) in R 4.3.2 using the glmmTMB and emmeans packages (Brooks et al. 2017; Lenth 2024; R Core Team 2023). For each metric, changes were examined separately for habitats and subregions, resulting in a total of eight models; this approach was used because sample sizes were too low to examine both habitat and subregion in one model. All models followed the same structure. Each metric was modeled using year, habitat or subregion, and their interaction as fixed effects. Transects were included as a random effect in each model to account for the repeated measures survey design. For stony coral and octocoral abundance, a negative binomial distribution with a log link function was used. For stony coral LTA, a gamma distribution with a log link function was used, and for octocoral total height, a tweedie distribution with a log link function was used. For each model, a pair-wise post hoc analysis was conducted to examine changes at the habitat or subregion level. All statistical inference was made at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Temperature

Across the years 2011-2023, 2023 had more days above both temperature thresholds than any other year, with 75.1±1.3 days above 30.5°C and 14.0±3.0 days above 32.0°C. For the 30.5°C threshold, six groupings were apparent based on significant differences between the years (**Figure 2**). With the greatest number of days above the 30.5°C threshold, 2023 was in its own group, followed by 2015, the last severe bleaching year, and then 2022. For the 32.0°C threshold, three groupings were apparent based on significant differences between the years (**Figure 2**). Again 2023 stood alone, with significantly more days above the 32.0°C threshold compared to all other years (2011-2022).

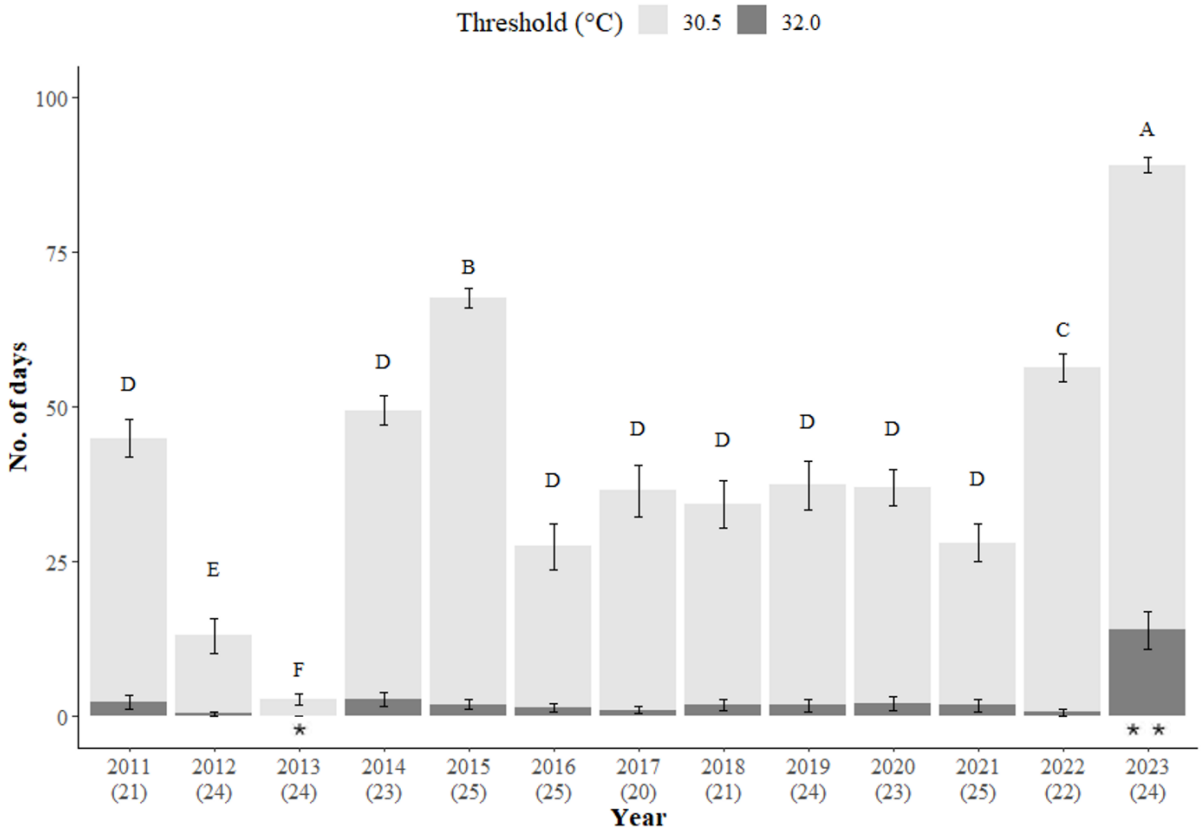

Figure 2. Mean number of days with temperatures over the coral mortality threshold of 32.0°C (dark grey) and the bleaching threshold of 30.5°C (light grey, inclusive of days over the mortality threshold) from 2011 to 2023 at 20-25 CREMP sites throughout the Florida Keys. The sample size of sites with temperature loggers per year is indicated in parentheses. Significant differences among the years are indicated by the letters above the bars for the 30.5°C threshold and by asterisks below the bars for the 32.0°C threshold. For the 30.5°C threshold, each temperature grouping decreases after letter "A". For the 32.0°C threshold, the double asterisk (**) was significantly higher than in all other years, the single asterisk (*) was significantly lower than in all other years; all other years were not significantly different from each other.

The mean number of days calculated for both thresholds only included data between the months of July through October because that is the time of peak thermal stress. In 2023, bottom-water temperatures began to rise above the bleaching threshold in early June, and therefore, the temperature stress in 2023 was worse than what is depicted in **Figure 2**, due to the early onset of elevated bottom-water temperatures prior to July.

Compared to the last severe bleaching event in 2015, 2023 had seven times more days above the 32.0°C threshold, highlighting the severity of the event. Despite having the third highest number of days above the 30.5°C threshold, results from the DRM surveys did not indicate that 2022 was a severe bleaching year. Looking at the number of days above the 32.0°C mortality threshold, 2022 had the third fewest, which may explain why it was not a severe bleaching year compared to 2015 and 2023.

Because 2015 had the second highest number of days above the 30.5°C threshold and was the last severe bleaching event prior to 2023, temperatures were compared between 2015 and 2023 across the subregions and habitats to better understand how the two bleaching events differed spatially.

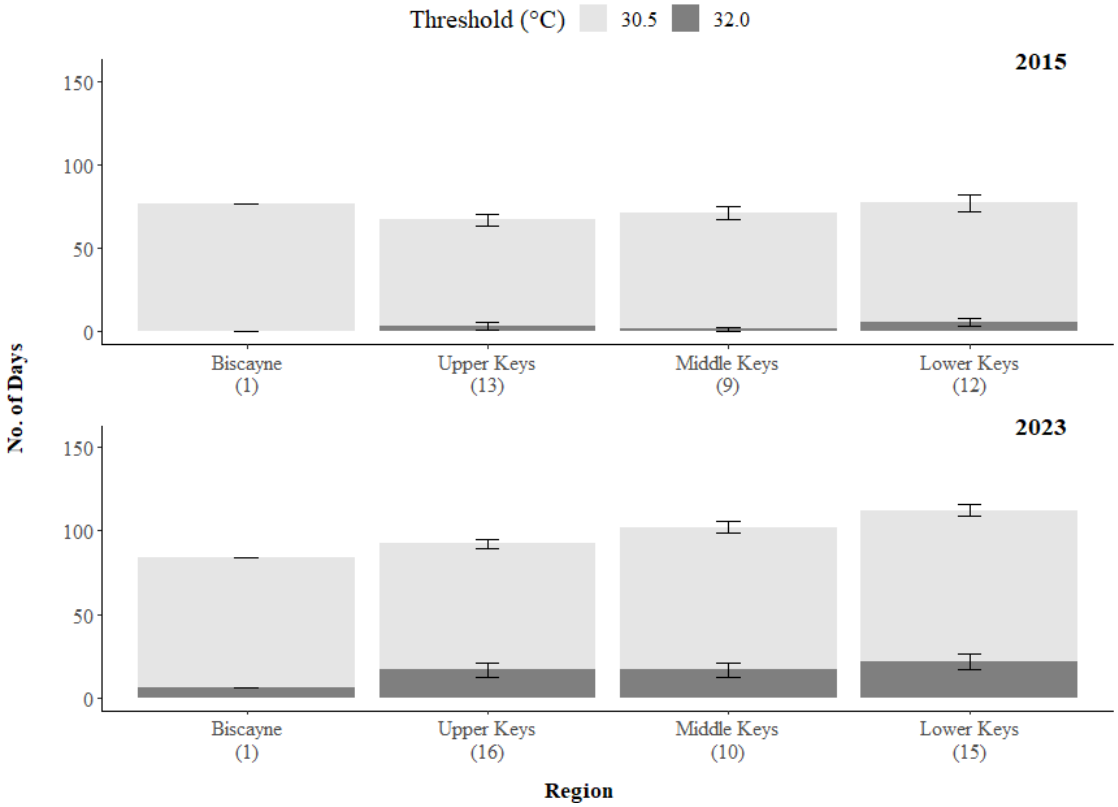

Figure 3. Mean number of days with temperatures over the coral mortality threshold of 32.0°C (dark grey) and the bleaching threshold of 30.5°C (light grey, inclusive of days over the mortality threshold) across regions for 2015 and 2023. The sample size of sites with temperature loggers per region is indicated in parentheses.

Across all four subregions, there were considerably more days above both the 30.5°C and 32.0°C thresholds in 2023 compared to 2015 (**Figure 3**). Temperature severity in 2023 followed a geospatial pattern through the Florida Keys, with the highest number of days above both thresholds in the Lower Keys and decreasing across the Keys moving northward. Although the Biscayne subregion had a similar number of days as the Upper Keys above the 30.5°C threshold, it had the fewest number of days above the 32.0°C threshold. Temperatures in 2015 followed a similar geospatial pattern as 2023 in the Florida Keys, where the Lower Keys had more days above both thresholds than the Middle and Upper Keys. The Middle Keys in 2015, however, had fewer days above the 32.0°C threshold than the Upper Keys (**Figure 3**).

Differences across the four habitat zones (inshore, mid-channel patch, offshore patch, and forereef) were more apparent. Compared to 2015, 2023 had significantly more days above both the 30.5°C and 32.0°C thresholds (**Figure 4**). Across both severe bleaching years, the inshore habitat had the most days above both thresholds, with the number of days decreasing for habitat types moving away from shore (mid-channel patch > offshore patch > forereef). In 2023, with little precipitation

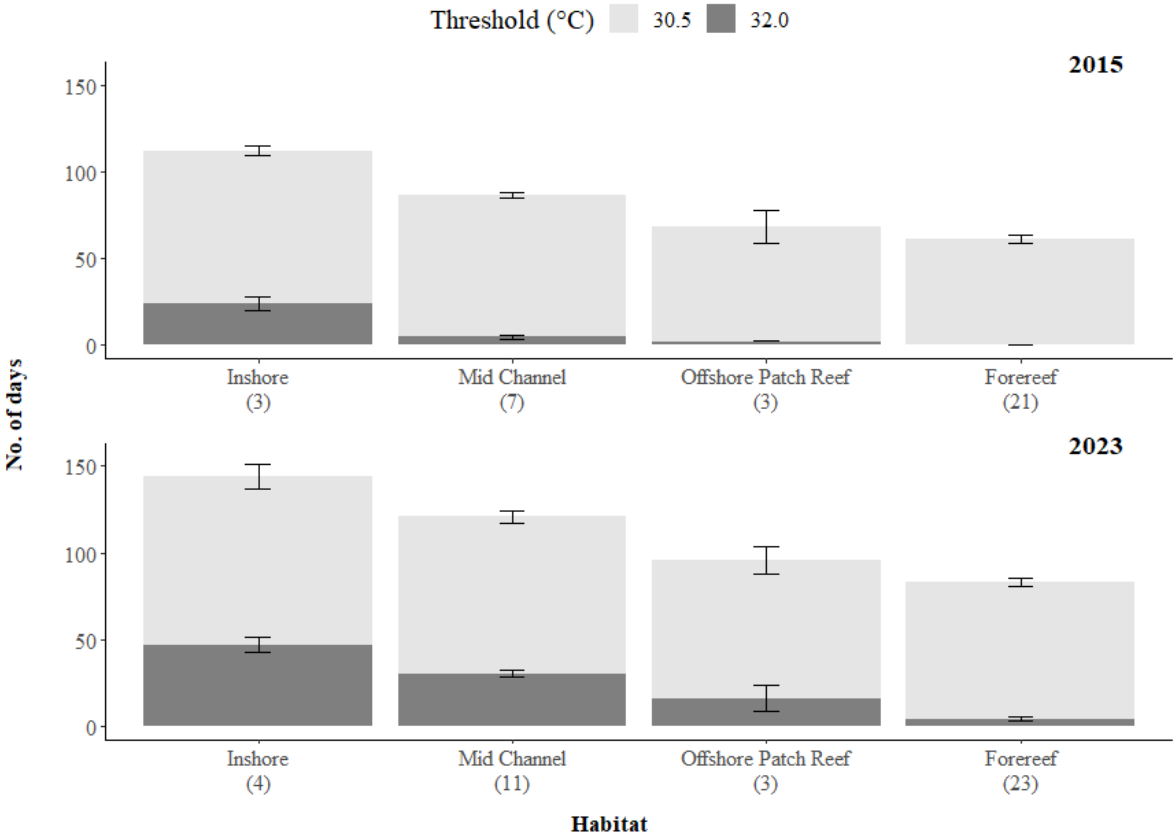

Figure 4. Mean number of days with temperatures over the coral mortality threshold of 32.0°C (dark grey) and the bleaching threshold of 30.5°C (light grey, inclusive of days over the mortality threshold) across habitat types for 2015 and 2023. The sample size of sites with temperature loggers per habitat is indicated in parentheses.

and light winds through the early summer, the shallow inshore waters off Biscayne and the Florida Keys heated up quickly, resulting in a greater number of days above both thresholds on the inshore reef and adjacent mid-channel patch reefs. In addition, across most of the Florida Keys, warm water from shallow Florida Bay likely flowed onto the inshore reefs with each outgoing tide, further increasing temperatures and prolonging thermal stress. Farthest from shore, the forereefs likely experienced some mixing of cooler Gulf Stream waters, minimizing the number of days above both thresholds compared to the other habitats.

Coral

From January 15th to March 31st, 2024, FWRI, along with six partner organizations, revisited 23 CREMP sites and 37 summer DRM sites where temporary markers were installed for post-bleaching surveys. In total, 81 transects were successfully located and surveyed, covering the Biscayne, Upper Keys, Middle Keys, and Lower Keys subregions. Pooled for each subregion, six transects were surveyed in Biscayne, 19 in the Upper Keys, 23 in the Middle Keys, and 33 in the Lower Keys (**Appendix I**). Pooled within each reef zone, nine transects were surveyed on the inshore reefs, 35 on the mid-channel reefs, four on the offshore patch reefs, and 31 on the forereefs.

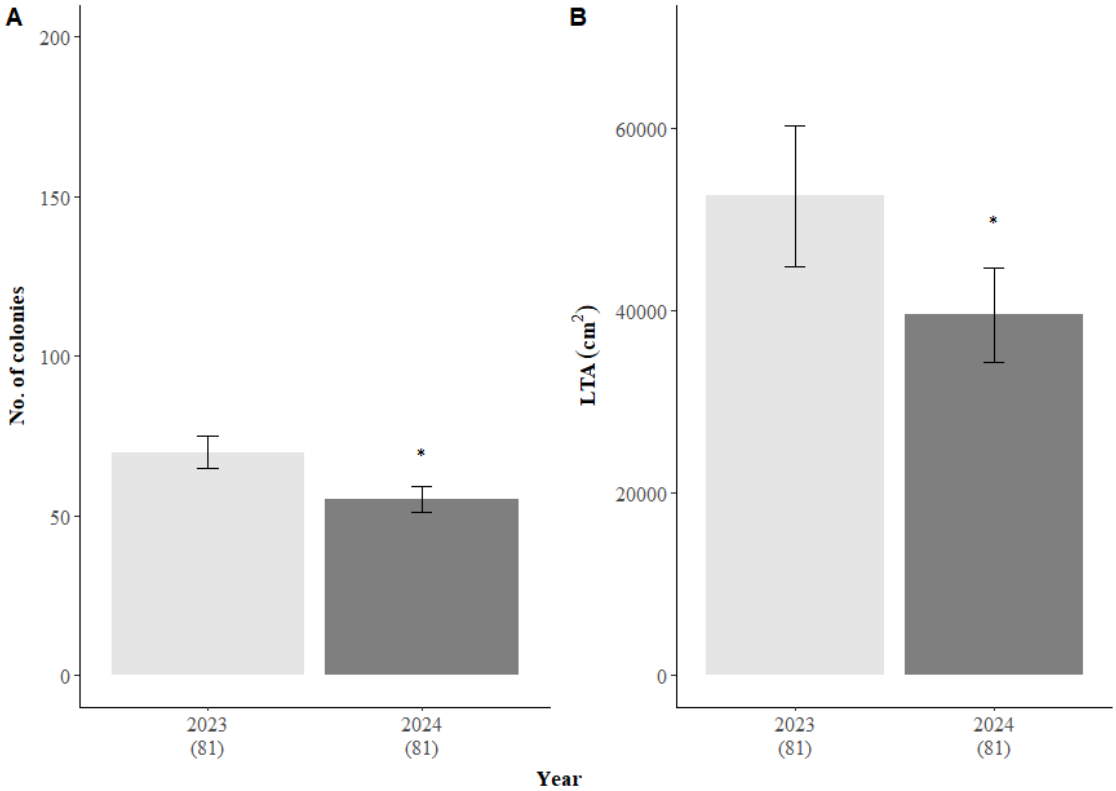

Figure 5. Mean coral colony abundance (**A**) and live tissue area (LTA) (**B**) per transect (n = 81) calculated from the 2023 summer DRM and CREMP surveys and the 2024 post-bleaching surveys. The asterisk (*) indicates a significant difference ($p < 0.05$) as determined by generalized linear mixed models.

Pooled for the 81 transects, there was a significant decline in mean coral abundance between the summer of 2023 and early 2024 (**Figure 5A**), with a 21% decrease (n = 1,205 corals) in the population. Additionally, pooled across all subregions and reef zones, mean live tissue area (LTA) was also significantly lower in 2024 than 2023 (**Figure 5B**). It should be noted that some CREMP and all DRM 2023 summer surveys took place after the coral mortality threshold had already been reached in June and July. Therefore, post-bleaching surveys may not have captured the total loss from the event, which should be considered when interpreting these results.

By subregion, mean coral abundance declined significantly from 2023 to 2024 in the Upper Keys, Middle Keys, and Lower Keys (**Figure 6A**). Coral abundance declined in the Biscayne subregion from 2023 to 2024, but the loss was not significant (p = 0.36). Mean LTA, however, was significantly lower across all four subregions from 2023 to 2024 (**Figure 6B**). Among the subregions, the Upper Keys had the greatest change in mean coral abundance (28% decline) and the Lower Keys subregion had the greatest change in LTA (29% decline).

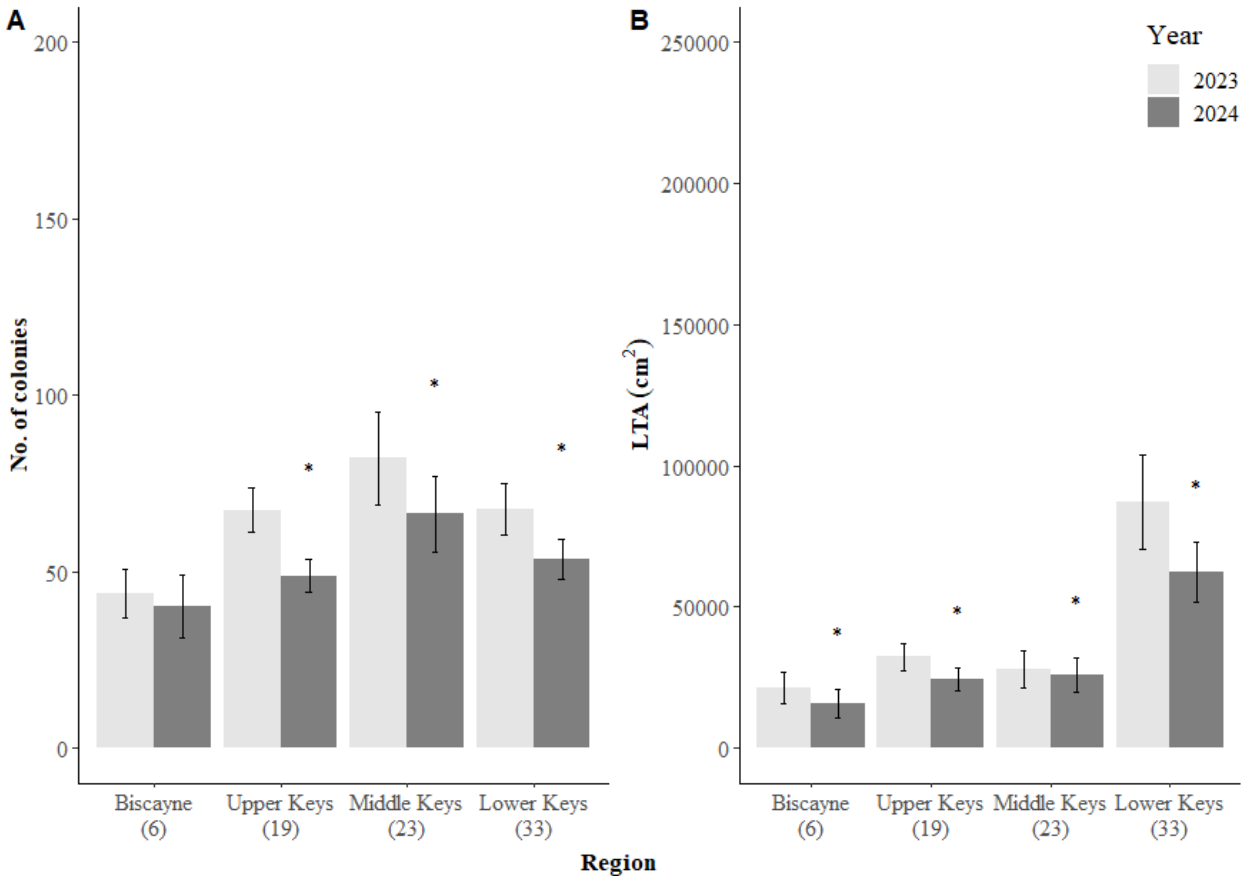

Figure 6. Mean coral colony abundance (**A**) and live tissue area (LTA) (**B**) per transect (n = 81) calculated from the 2023 summer DRM and CREMP surveys and the 2024 post-bleaching surveys across the four regions. The asterisk (*) indicates a significant difference (p < 0.05) as determined by generalized linear mixed models. The sample size of transects per region is indicated in parentheses.

By reef habitat, mean coral abundance and mean LTA were significantly lower across all habitats from 2023 to 2024 (**Figure 7**). The inshore reef, mid-channel patch reefs, and offshore patch reefs all had a >20% decline in total abundance, while the decline at the forereef, farthest from shore, was 18%.

The species most impacted by the event were those with a low bleaching tolerance, as reflected by high bleaching prevalence values during the 2023 summer surveys (2023 DRM Summer Quick Look Report). When pooled for the entire reef tract, the highest bleaching prevalence values were 93% for *Agaricia* spp., 92% for the branching *Porites* spp. complex, and 73% for *P. astreoides.* In the 2024 post-bleaching surveys, *Agaricia* spp. were reduced in number by 376 colonies (74% decline), branching *Porites* spp. by 146 colonies (47% decline), and *P. astreoides* by 526 colonies (47% decline), pooled across the four subregions (**Appendix II**).

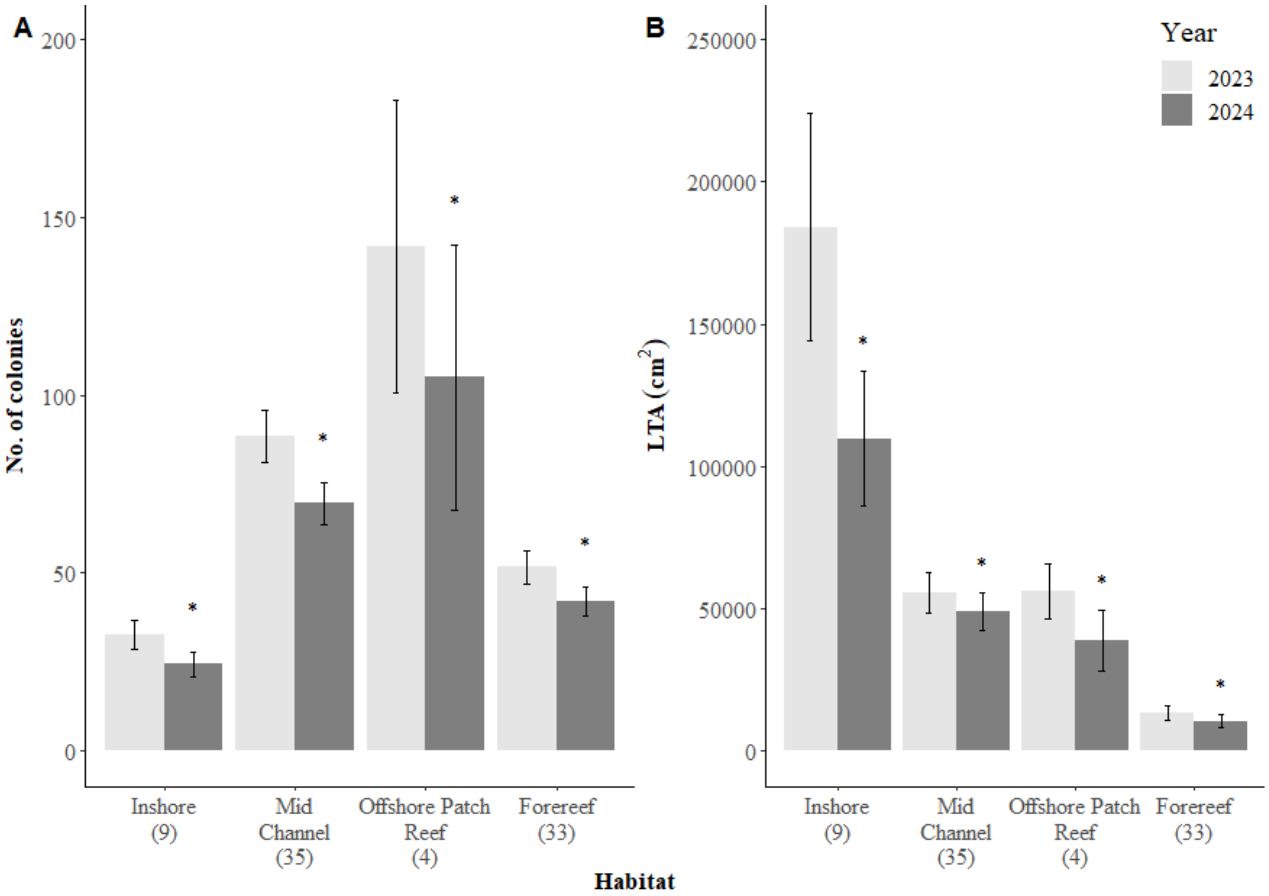

Figure 7. Mean coral colony abundance (**A**) and live tissue area (LTA) (**B**) per transect (n = 81) calculated from the 2023 summer DRM and CREMP surveys and the 2024 post-bleaching surveys across the four habitat types. The asterisk (*) indicates a significant difference ($p < 0.05$) as determined by generalized linear mixed models. The sample size of transects per habitat is indicated in parentheses.

By subregion, *Agaricia* spp. and branching *Porites* spp. had higher abundances in the Upper Keys in 2023 than the other three subregions, which relates to the decline in abundance in that subregion between 2023 and 2024. The significant declines in LTA in the Lower Keys were partially driven by the greater abundance of larger corals between 50cm to 100cm in diameter in 2023. For example, among the larger reef building species, the abundance of *Orbicella* spp. was four to six times higher in the Lower Keys in 2023 than in the other subregions and declined by 15% between the summer and post-bleaching survey periods. In addition to the complete loss of many *Orbicella* spp. colonies in the Lower Keys, those colonies that survived suffered extensive partial mortality. The average partial mortality per colony increased nearly 20% between the summer 2023 and post-bleaching surveys. The complete or partial loss of these large colonies and their disproportional contribution to LTA likely contributed to the higher loss of LTA in the Lower Keys.

Some coral species recovered surprisingly well from the bleaching event. One of the most abundant species in FCR, *Siderastrea siderea,* only declined by 1% (pooled for all transects) from 2023 to 2024 (**Appendix II**), and there was little change in the LTA of this species. Other highly abundant species that only had small changes in abundance and LTA were *Montastraea cavernosa,* which declined by 1% in abundance and 3% in LTA, and *Stephanocoenia intersepta,* which declined by 5% in abundance and 3% in LTA. Bleaching prevalence values during the 2023 summer surveys for *S. siderea, M. cavernosa*, and *S. intersepta* were 51%, 62% and 46% respectively, highlighting their ability to recover, as almost half or more of their population was bleached.

Octocoral

At 19 CREMP sites, FWRI surveyed 38 total transects (two transects per site) for post-bleaching octocoral demographics. Pooled across subregion, 10 transects were surveyed in the Upper Keys, 16 in the Middle Keys, and 12 in the Lower Keys. Pooled across habitat, 12 transects were surveyed at patch reefs, 14 at shallow forereefs, and 12 at deep (~35-50ft) forereefs.

Overall, pooled for the 38 transects, there were 2,384 fewer octocorals in early 2024 compared to the summer of 2023, resulting in a significant 37% decline in total octocoral abundance (**Figure 8A**). Similarly, the mean sum of target species colony heights was significantly lower in 2024 than in 2023, declining by 40% (**Figure 8B**).

By subregion, mean octocoral abundance and target species colony heights were both significantly lower in the Upper and Middle Keys in the post-bleaching period compared to the summer of 2023 (**Figure 9**). Among the subregions, the largest decline in total octocoral abundance was in the Upper Keys (45%) and the largest decline in the sum of the target species colony heights was in the Middle Keys (43%). In the Lower Keys, both metrics declined, but neither were significant ($p = 0.07$ and $p = 0.10$). This is an interesting result, since the Lower Keys had the greatest number of days above both the 30.5°C threshold and the 32.0°C threshold compared to the Upper and Middle Keys. This may represent a greater tolerance to thermal stress within the octocoral

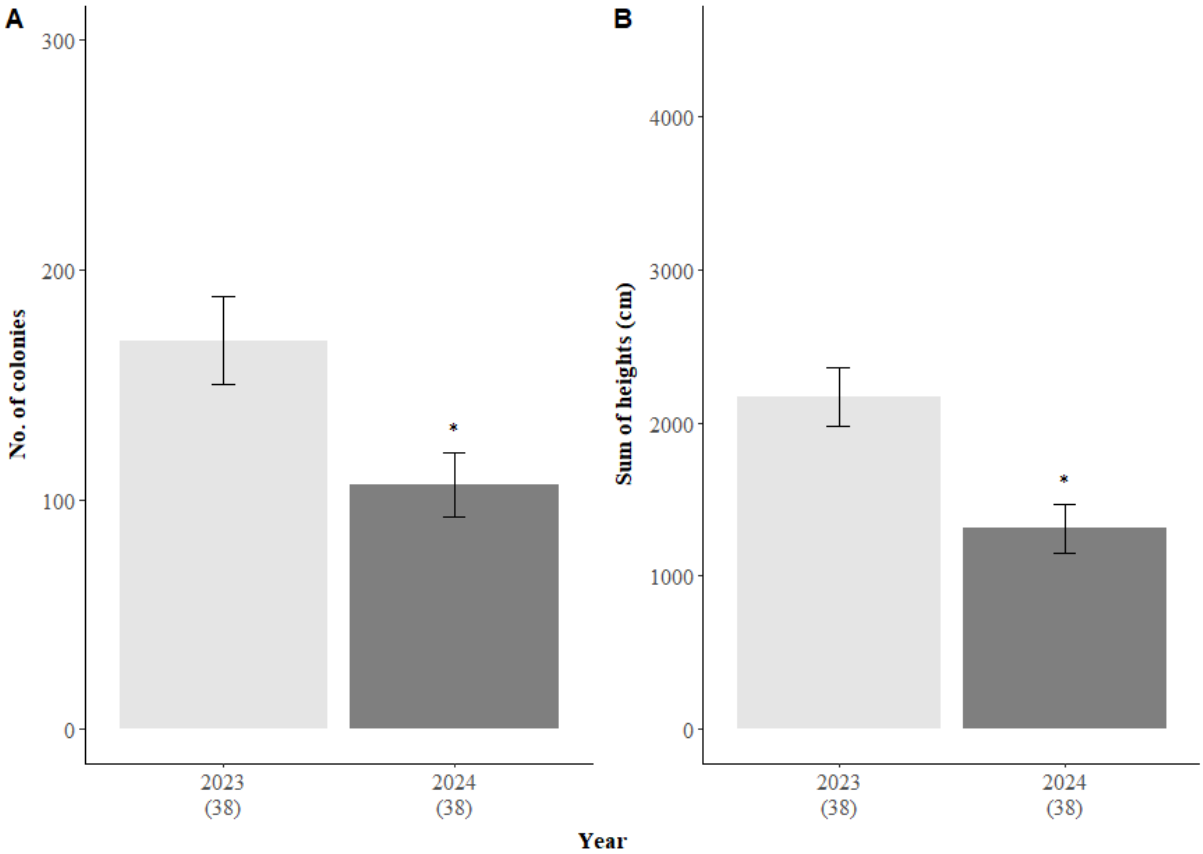

Figure 8. Mean octocoral colony abundance (**A**) and sum of target species colony heights (cm) (**B**) per transect (n = 38) calculated from the summer 2023 and 2024 post-bleaching CREMP surveys. The asterisk (*) indicates significance ($p < 0.05$) as determined by generalized linear mixed models.

population in the Lower Keys but may also be an artifact resulting from the lower abundance of octocorals on the patch reefs in the Lower Keys, which endured the greatest exposure to elevated water temperatures, and larger populations on the deeper forereefs, which had less octocoral mortality than on patch reefs.

By reef habitat, mean octocoral abundance and target species colony heights did not change significantly at deep forereefs ($p = 0.21$ and $p = 0.26$, respectively; **Figure 10**). In contrast, at patch reefs, both metrics significantly and drastically declined, representing a 74% decrease in arborescent octocoral abundance and an 80% decrease in the sum of target species colony heights. Although there was a significant decline in total octocoral abundance (~ 33%) between the summer of 2023 and early 2024 at the shallow forereefs (**Figure 10A**), it did not correspond with a significant decrease in the sum of the heights of the target species ($p = 0.37$; **Figure 10B**). There may be several reasons that explain this apparent disparity, including more whole colony mortality among non-target species, resulting in little change in the sum of the heights of the target species, or that mortality among the target species was more acute on small colonies, which add

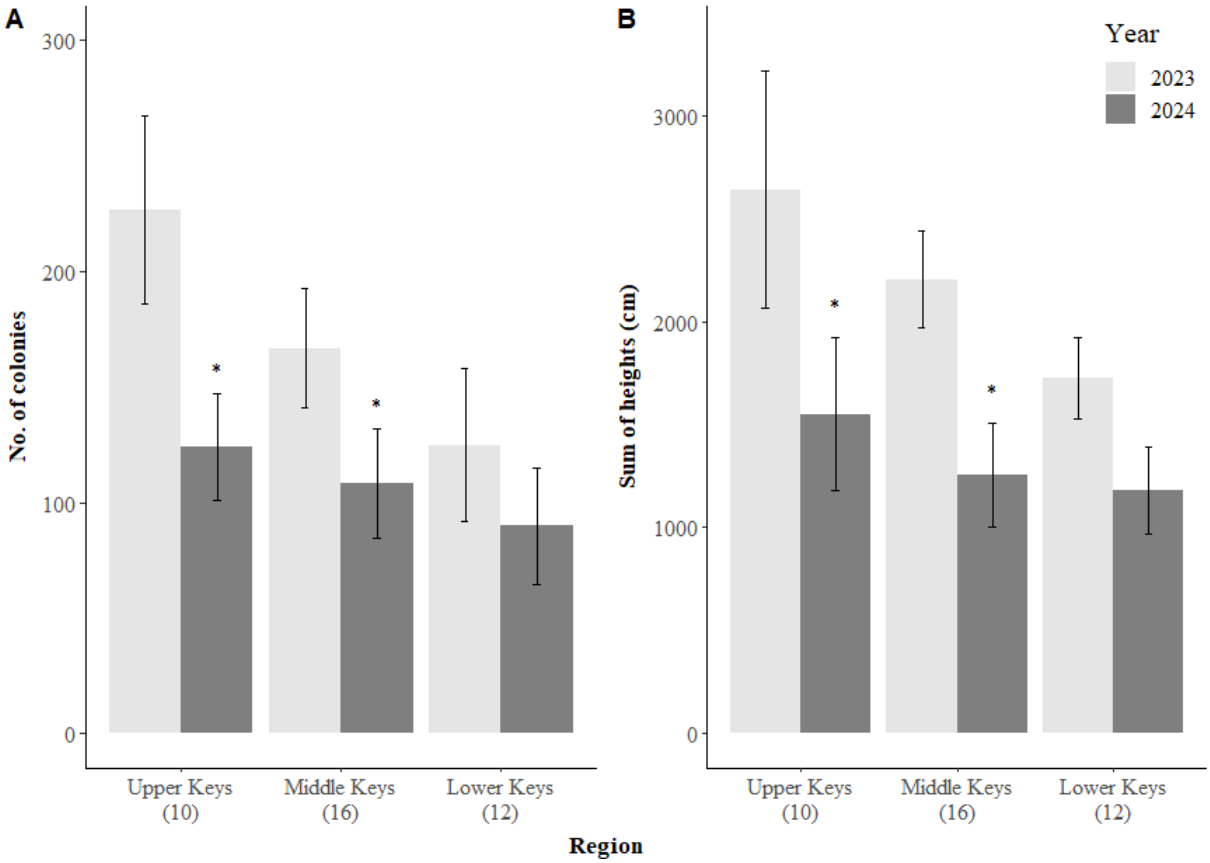

Figure 9. Mean octocoral colony abundance (**A**) and sum of target species colony heights (cm) (**B**) per transect (n = 38) calculated from the summer 2023 and 2024 post-bleaching CREMP surveys across three subregions. The asterisk (*) indicates significance ($p < 0.05$) as determined by generalized linear mixed models. The sample size of transects per region is indicated in parentheses.

relatively little to the sum of the height. Examination of the size classes of the target species and their relative contribution to the overall abundance within this habitat was outside the scope of this analysis but could enhance our understanding of this event.

All CREMP target octocoral species declined by 24% or more in overall abundance from 2023 to 2024 (**Appendix III**). Notably, *Pseudoplexaura porosa* declined by 91%; however, the total abundance of this species in 2023 was less than 50 colonies. The most common CREMP target species, *Antillogorgia americana*, decreased by 582 colonies, representing a 31% decline of the surveyed population. *Gorgonia ventalina* decreased by 373 colonies, *A. bipinnata* by 117 colonies, and *Eunicea flexuosa* by 70 colonies, resulting in 24%, 38%, and 29% declines, respectively.

A few interesting patterns emerged at the habitat and regional levels among the CREMP target octocoral species. The majority (42 of 45) of *P. porosa* colonies surveyed in 2023 were at patch reefs, which endured higher temperatures than the forereefs; however, the three colonies found at

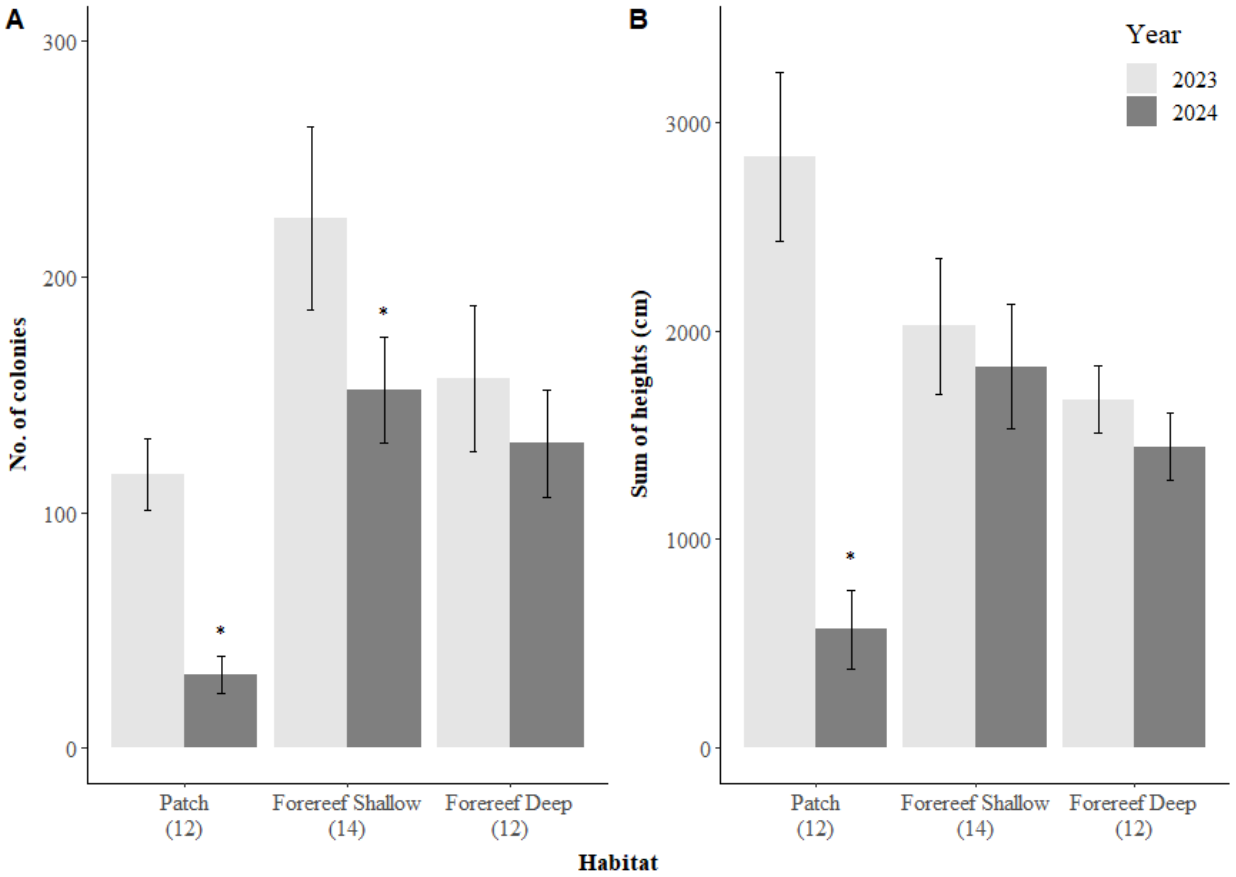

Figure 10. Mean octocoral colony abundance (**A**) and sum of target species colony heights (cm) (**B**) per transect (n = 38) calculated from the summer 2023 and 2024 post-bleaching CREMP surveys across three habitat types. The asterisk (*) indicates significance ($p < 0.05$) as determined by generalized linear mixed models. The sample size of transects per habitat is indicated in parentheses.

the forereefs (deep and shallow combined) in 2023 also were not found in 2024. The largest declines in abundance for three of the other target species were also at patch reefs: 81% for *A. americana*, 80% for *G. ventalina*, and 48% for *E. flexuosa*. All three of these species are distributed across the three CREMP habitats, and they all declined at the shallow and deep forereef habitats as well as at patch reefs. The only exception was for *G. ventalina*, which increased in abundance by 38% at the deep forereefs, possibly due to a recruitment event. In contrast, *A. bipinnata*, which is found almost exclusively at the deep forereefs, declined by 28% in this habitat, especially in the Middle Keys, where this species declined by 70%. Despite the deep forereef not experiencing a significant decline in total octocoral abundance, the decline in *A. bipinnata* abundance suggests that there may have been some species-specific impacts of this thermal stress event, even in habitats or regions where the thermal stress was not as extreme as others.

SUMMARY

Temperature

To illustrate the intensity of the 2023 thermal stress event, the mean number of days bottom-water temperatures were above the bleaching threshold of 30.5°C and the coral mortality threshold of 32.0°C were compared over the 13-year period of 2011-2023. The mean number of days above both thresholds was significantly greater in 2023 than in any of the previous 12 years analyzed. Compared to the most recent severe bleaching year in 2015, 2023 had seven times more days above the 32.0°C mortality threshold. Although 30.5°C has traditionally been accepted as the threshold to trigger a bleaching event in Florida, the 32.0°C threshold may prove better at distinguishing the differences in severity. As an example, in 2022, the third highest number of days above the 30.5°C threshold was recorded, but the third fewest number of days above the 32.0°C threshold was recorded. This may partially explain lower bleaching prevalence values in 2022 and why it was not considered a severe bleaching year by the DRM program. Overall, the duration and severity of high bottom-water temperatures above the 32.0°C threshold in 2023 provides evidence to why this bleaching event was so unparalleled compared to recent history and provides context for the significant losses seen in both the coral and octocoral communities on Florida's Coral Reef.

Coral

The losses in mean coral colony abundance and mean live tissue area (LTA) across the survey regions and habitats resulting from the bleaching event were widespread. The three subregions in the Florida Keys (Upper, Middle, and Lower) all demonstrated significant declines in abundance and LTA. Although Biscayne declined in both abundance and LTA as well, only the change in LTA was significant. Among the post-bleaching subregions, the Upper Keys had the greatest decline in coral abundance while the Lower Keys had the greatest decline in LTA.

Most impacted by the event were those species with a low bleaching tolerance, often found in high abundance in most habitats: *Agaricia* spp., branching *Porites* spp., and *P. astreoides*. With the early onset of high-water temperatures in June of 2023, these species experienced a prolonged period of bleaching, resulting in higher mortality rates. Some coral species showed greater resilience to the bleaching event, with only small losses to their populations. While almost half or more of their population experienced bleaching in 2023, *Siderastrea siderea*, *Montastraea cavernosa*, and *Stephanocoenia intersepta* each only lost 5% or less of their surveyed population and 3% or less LTA from the bleaching event.

Octocoral

Pooled across subregions and habitats, the overall loss of octocoral abundance and the decline in the sum of target species heights between 2023 and 2024 were significant. Mean octocoral abundance declined by 37% with a similar corresponding decline of 40% in the sum of target

species heights. Significant declines were confirmed for both the Upper and Middle Keys subregions and in the patch and shallow forereef habitats. The greatest declines in abundance and sum of target species heights were recorded at the patch reefs, where abundance and the sum of target species heights decreased by 74% and 80%, respectively. This pattern was driven by the higher number of days above the coral bleaching and mortality thresholds observed at the patch reefs, especially those in the Middle Keys. Although there were a smaller number of days above the coral bleaching and mortality thresholds recorded at the forereefs than at the patch reefs, the elevated temperatures were still strong enough to incur significant reductions in octocoral abundance at the shallow forereefs and large declines, albeit not significant, at the deep forereefs. Besides the community-wide declines in abundance, the vulnerability of some species to thermal stress led to large reductions in their population size across the Florida Keys. All five species targeted in the CREMP octocoral surveys declined by >20% in abundance, with mortality rates as high as 91% for *Pseudoplexaura porosa* and 38% for *Eunicea flexuosa*. The acute impacts to the octocoral population presented here confirm that the effects of the 2023 thermal stress event went well beyond those experienced by stony corals and were deleterious to the wider coral reef community.

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APPENDICES

Appendix 1. Number of coral and octocoral transects per subregion, zone, and project at which post-bleaching surveys were conducted. Stony coral analyses of habitat follow the DRM habitat zones of forereef (combined deep and shallow as presented in this table), offshore patch, mid-channel patch, and inshore patch. Octocoral analyses follow the CREMP habitat zones of forereef deep, forereef shallow, and patch reef (combined mid-channel and offshore patch reef as presented in this table). Note there are no CREMP sites in the Biscayne subregion, so octocoral surveys were not conducted there.

Subregion	Zone	Project	Number of coral transects	Number of octocoral transects
Biscayne	Mid-Channel	DRM	5	0
Biscayne	Forereef	DRM	1	0
Upper Keys	Mid-Channel	DRM	5	0
Upper Keys	Mid-Channel	CREMP	4	2
Upper Keys	Offshore Patch Reef	DRM	2	0
Upper Keys	Offshore Patch Reef	CREMP	2	2
Upper Keys	Forereef deep	CREMP	2	2
Upper Keys	Forereef shallow	CREMP	4	4
Middle Keys	Mid-Channel	DRM	7	0
Middle Keys	Mid-Channel	CREMP	2	2
Middle Keys	Offshore Patch Reef	CREMP	2	2
Middle Keys	Forereef deep	CREMP	6	6
Middle Keys	Forereef shallow	CREMP	6	6
Lower Keys	Inshore	DRM	9	0
Lower Keys	Mid-Channel	DRM	6	0
Lower Keys	Mid-Channel	CREMP	6	4
Lower Keys	Forereef deep	CREMP	6	4
Lower Keys	Forereef shallow	CREMP	6	4
Total number of transects			81	38

Appendix II. Total abundance of colonies by species recorded during the 2023 summer survey and the 2024 post-bleaching survey, as well as their total decrease or increase, in number and percent of colonies, between the two survey events.

Species	2023 total abundance	2024 total abundance	Total decrease in colonies	Percent decrease in colonies
Siderastrea siderea	2093	2069	24	1
Porites astreoides	1129	603	526	47
Stephanocoenia intersepta	791	751	40	5
Agaricia spp.	507	131	376	74
Branching *Porites* spp.	312	166	146	47
Montastraea cavernosa	287	285	2	1
Orbicella spp.	277	235	42	15
Siderastrea radians	78	65	13	17
Colpophyllia natans	42	39	3	7
Dichocoenia stokesii	28	22	6	21
Madracis spp.	18	8	10	56
Mycetophyllia spp.	18	10	8	44
Eusmilia fastigiata	15	15	0	0
Solenastrea bournoni	13	13	0	0
Manicina areolata	8	2	6	75
Pseudodiploria clivosa	7	7	0	0
Helioseris cucullata	6	0	6	100
Scolymia spp.	2	2	0	0
Favia fragum	1	0	1	100
Phyllangia americana	1	1	0	0
Species	**2023 total abundance**	**2024 total abundance**	**Total increase in colonies**	**Percent increase in colonies**
Pseudodiploria strigosa	17	18	1	6
Diploria labyrinthiformis	14	15	1	7
Meandrina meandrites	1	3	2	200

Appendix III. Decrease of CREMP survey target octocoral species between the 2023 summer surveys and the 2024 post-bleaching surveys, as well as their total decrease, in number and percent of colonies, between the two survey events.

Species	2023 total abundance	2024 total abundance	Total decrease in colonies	Percent decrease in colonies
Pseudoplexaura porosa	45	4	41	91
Eunicea flexuosa	182	112	70	38
Antillogorgia americana	1872	1290	582	31
Antillogorgia bipinnata	402	285	117	29
Gorgonia ventalina	1586	1213	373	24