

Mapping Coral Health Dynamics at Cheeca Rocks (2012–2018)

--A Colony-Level Analysis of Bleaching, Spatial Structure, and Mortality Using High-Resolution Photomosaics

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Abstract

High-resolution mosaic images and spatially matched polygon data were taken from Cheeca Rocks transect 1 (2012–2014); these data were used to examine spatial structure, bleaching responses, and short-term death rates at the colony level for four coral taxa: *Orbicella annularis* (OANN, formerly MANN), *Porites astreoides* (PAST), *Porites porites* (PPOR), and *Siderastrea siderea* (SSID); TagLab annotations, nearest-neighbor distance calculations in ArcGIS Pro, and bleaching and death metrics generated in R Studio were combined, and changes in the coral community at the scale of individual colonies were recorded. The results showed that 2014 had the strongest bleaching during the study period; in September 2014, nearly 100% of OANN and PPOR colonies were bleached, PAST was around 20%, and SSID stayed at 0% in all surveys; the death patterns followed the same trend, OANN and PAST decreased over the whole study period, and PAST had the largest loss (–25%) between 2013 and August 2014, while PPOR had a moderate decline (–11.4%) during the same time and no death was recorded for SSID; for colony spacing, only OANN showed clear differences in the average distance to nearest neighbor, and the other species kept relatively stable spacing patterns from 2012 to 2014. Overall, it was shown by the results that the high temperature event in 2014 was the main reason for the bleaching and population loss at Cheeca Rocks; at the same time, the ability of each species to tolerate heat was a key factor in deciding how the coral community responded; when the 2015–2018 aligned photomosaic layers are added in future work, it will be possible to look more completely at long-term recovery, changes in spatial arrangement, and the effects of repeated disturbances under continued climate stress.

Keywords

Coral bleaching, mortality, spatial structure, photomosaics, TagLab; ArcGIS Pro, Cheeca Rocks, thermal stress.

1. Introduction

Coral reefs were one of the most important marine ecosystems in the world from both ecological and economic points of view; however, in recent decades, they had been under increasing pressure because the ocean was warming and heat stress events were becoming more frequent; mass bleaching had been documented in many regions, and both the severity and how often these events happened kept increasing [1, 2]. In the Florida Keys, long-term declines in coral cover were caused by repeated heatwaves, disease outbreaks, and localized coral death; the 2014 temperature anomaly was widely seen as a major disturbance event, and it caused considerable bleaching and coral death across the region [3, 4]. Many studies looked at changes at the community level, but fewer studies checked how bleaching and death were

different from one coral colony to another, or whether these responses had any connection with the fine-scale spacing patterns of corals.

Coral reefs were considered one of the most important marine ecosystems in the world in both ecological and economic terms; however, in recent decades, the pressure on them had been getting greater because the ocean was warming and heat stress events were happening more often; mass bleaching was recorded in many regions, and the severity and how often these events happened kept going up [1, 2]; in the Florida Keys, repeated heatwaves, disease outbreaks, and localized coral death caused coral cover to decline over the long term; the 2014 thermal anomaly was widely seen as a major disturbance event, and significant bleaching and mortality were caused by it throughout the region [3, 4]; while many studies focused on changes at the community level, fewer studies checked how bleaching and death were different from one coral colony to another, or whether these responses had any connection with the fine-scale spacing patterns of corals.

In order to fill these gaps, the work looked at bleaching, death, and changes in spatial arrangement at the colony level at Cheeca Rocks Transect 1 from 2012 to 2014; the data included four main coral species, which were *Orbicella annularis* (OANN), *Porites astreoides* (PAST), *Porites porites* (PPOR), and *Siderastrea siderea* (SSID); three hypotheses were tested:

H1 was that coral species responded to heat stress in different ways, producing bleaching and death patterns that were specific to each species;

H2 was that the spatial arrangement of colonies changed over time, and these changes were not the same among species;

H3 was that colonies that were located closer together had health outcomes that were more alike, especially in bleaching.

To examine these hypotheses, TagLab polygon labels were used to mark each coral colony, the distance from each colony to its closest neighbor and other location data were calculated with ArcGIS Pro, and R Studio was used for the analyses of bleaching, death, and correlation; by using this workflow, it was possible to check the vulnerability of each species during the 2014 bleaching event, to find out whether the spatial pattern changed over time, and to test whether bleaching showed signs of being grouped in space.

In addition to the ecological results, this project also showed a repeatable “TagLab–ArcGIS–R” workflow, and this workflow could be used for the future photomosaic layers from 2015–2018; including these extra years would make it possible to analyze the recovery after bleaching, the effects of repeated disturbances, and the long-term changes in spatial structure; in the end, the results given here could help to identify high-risk species, improve the understanding of community stability, and provide spatial information for coral conservation and management.

2. Materials and Methods

2.1. Study Area and Data Sources

From 2012 to 2014, this project examined how the spatial arrangement, bleaching intensity, and death patterns of coral communities at Cheeca Rocks in the Florida Keys Reef Tract changed over time; Cheeca Rocks was located within the Florida Keys National Marine Sanctuary (about 24.92°N, 80.62°W), and it was a shallow reef with high light that was known for its uncommon ability to recover and for its long-term value in ecological monitoring.

The main data used in this study came from the long-term photomosaic program described in Gintert et al. [3]; these data included coral outlines made with TagLab, species codes, individual colony labels, and initial health classifications. Annual orthomosaic imagery and spatially aligned vector layers were contributed by Dr. Arthur C. R. Gleason, who ensured that transect boundaries from different survey years were accurately co-registered and suitable for precise

cross-year comparisons. The full monitoring design at Cheeca Rocks consisted of six long-term photomosaic transects; in this study, I focused on Transect 1 as a first step toward a more complete analysis of the full six-transect dataset.

Additional attribute fields relevant to this project were generated using ArcGIS Pro. These included nearest-neighbor identifiers, nearest-neighbor distances, numeric species codes, bleaching flags, and parent-colony relationships. These derived fields formed the analytical database used for all spatial and statistical computations.

2.2. Software and Analytical Tools

Image interpretation, spatial data processing, and statistical analysis were conducted using a combination of software platforms.

To check and confirm the polygon notes that were first made for each coral colony, TagLab was used; the spatial edges of the colonies and the starting health condition labels were also given by TagLab.

All spatial processing work was done with ArcGIS Pro, including bringing in vector layers, checking that the alignment was the same across years, changing and making uniform the attribute tables, working out the distance to the closest neighbor, and showing the spatial patterns over several years.

Microsoft Excel was used to combine the attribute tables from different years, to put the data into a long form, to work out bleaching rates, and to sum up the statistics for each species.

The statistical analyses were run in R Studio; these included calculating death rates across survey periods, using a one-way analysis of variance (ANOVA) to test whether the mean distance to the closest neighbor changed between years within each species, and making boxplots, scatterplots, bleaching summary charts, and mortality visuals.

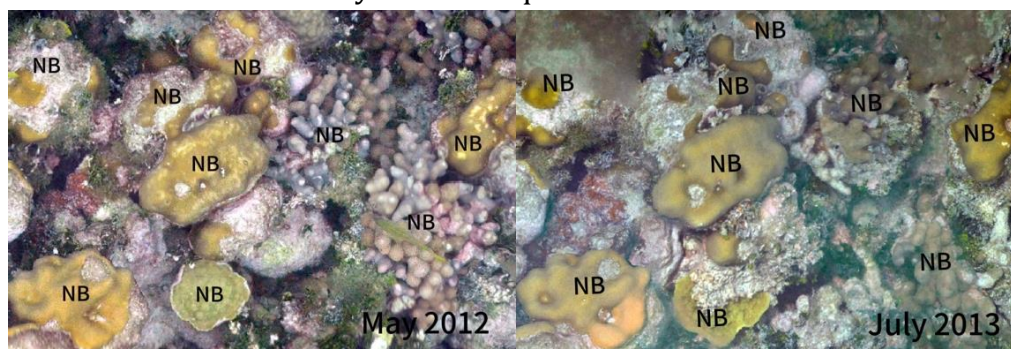
2.3. Workflow Overview

2.3.1. Organization of Data and Spatial Registration

The orthomosaic imagery and vector datasets for transect 1 (2012, 2013, and 2014) were brought into ArcGIS Pro; the spatial alignment had already been completed by the Gleason Lab, so all yearly layers could be overlaid within a unified coordinate system without additional georeferencing; the attribute tables were standardized across years to ensure consistent field structure before further processing.

2.3.2. Coral Annotation and Health Classification

The polygon labels used in this study came from the long-term photomosaic dataset that was made by Gintert et al. [3] in TagLab and then added to in this project; for each year's mosaic image, the existing polygon layer was used as a reference, and the colony edges were checked by hand, changed, and drawn again so that each colony was shown in the same way over time; new point layers were also made to follow what happened to colonies across years, and a point was put in the middle of each colony with a unique CoralID.



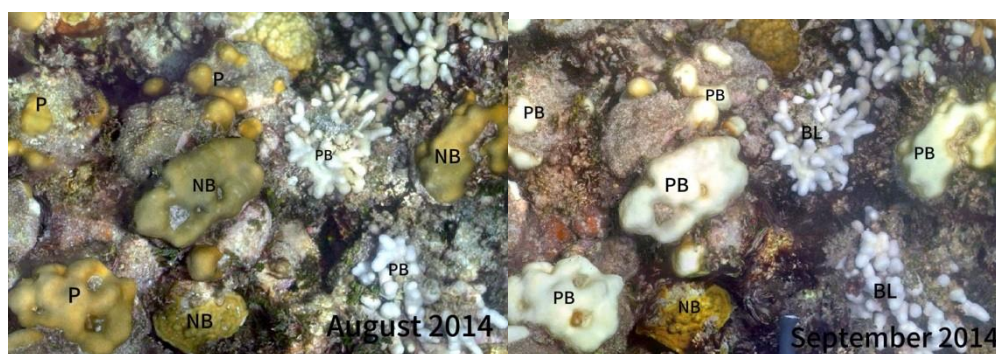


Figure 1. Shown here are representative examples of the bleaching levels (NB–BL) that were used in this study; these examples include colonies of several species and show the range of color changes that were observed across the surveys from 2012 to 2014; the labels on these examples match the bleaching-level groups that were used for the quantitative analysis throughout the study.

Health states were sorted into four bleaching groups depending on color and tissue brightness: NB (no visible bleaching), P (pale), PB (partially bleached), and BL (fully bleached); sample pictures that showed each bleaching level (NB, P, PB, BL) were added as Figure 1 to support the methods, and these pictures showed typical colonies from 2012 to 2014.

For the quantitative analysis, these qualitative scores were turned into number-based bleaching markers (0–3); a parent-colony field was used to link colonies that broke apart or joined together between survey years, and this made it possible to tell actual death apart from structural changes such as breakage, partial loss, or fusion among neighboring colonies.

2.3.3. Nearest-Neighbor Spatial Analysis

To quantify spatial structure within each species, straight-line distances from each colony to its nearest neighbor of the same species were calculated using the Near tool in ArcGIS Pro; these distances were grouped by species and year; a one-way ANOVA in R Studio was used to test whether the average nearest-neighbor distance for each species changed significantly between survey years, and this helped to check whether the spatial arrangement stayed stable or whether colonies became more spread out or closer together over time.

2.3.4. Mortality Analysis

To estimate death rates, colony fates were tracked across survey years; colonies were matched using unique identifiers, and those that were present at time t but absent at time $t+1$ were treated as dead under the “disappearance equals death” rule; parent-colony information helped avoid mistaking breakage or joining for death; death rates for each species were calculated for each survey interval and visualized in R.

2.3.5. Integrated Analysis and Visualization

In ArcGIS Pro, the final spatial layers were given symbols and exported so that the spatial patterns of colony distribution and bleaching could be shown; the ggplot2 package in R was used to make the statistical results, which included bleaching time series, bar charts of death rates, scatterplots comparing bleaching severity with the distance to the nearest neighbor, and boxplots for each species that showed spatial structure; together, these outputs served as the main support for the Results section and helped explain the spatial structure, bleaching severity, and death patterns within the coral community.

2.3.6. Additional Analysis: Pooled-Species Distance vs. Bleaching

When all species were pooled into one dataset, the nearest-neighbor distance and bleaching relationship was re-evaluated; this additional analysis tested whether the weak correlation

seen at the species level stayed consistent when the coral group was treated as a whole. A Spearman correlation test was used to evaluate the strength and direction of the relationship between average nearest-neighbor distance and bleaching severity across the entire assemblage; this pooled analysis helped to find out if spatial structure affected bleaching at the community scale or if bleaching was mostly driven by species identity.

Table 1. This table gives an overview of the coral colonies that were marked across all the photomosaic surveys at Cheeca Rocks from 2012 to 2014; the total colony counts stand for all the coral polygons that were labeled in TagLab and were used for tracking colonies, classifying bleaching, and calculating nearest-neighbor distances; these numbers set up the sampling design for the later bleaching, mortality, and spatial analyses.

Survey Year	Survey Month	Total Colonies Annotated	OANN	PAST	PPOR	SSID
2012	May	169	134	24	4	7
2013	July	149	116	22	4	7
2014	August	129	102	17	3	7
2014	September	119	94	15	3	7

3. Results

3.1. Coral Bleaching Temporal Patterns (2012–2014)

Bleaching severity was very different among the four coral species (OANN, PAST, PPOR, and SSID) over the 2012–2014 monitoring period, as shown in Figure 2; in 2012, bleaching was very low for all species, and it stayed very low in 2013; a clear increase happened in 2014, with bleaching getting much worse in August and peaking in September; OANN and PPOR were affected the most, and their bleaching rates rose to about 98% and 100% by September 2014, respectively; PAST had only a moderate level of bleaching, with its highest rate near 20%, while SSID stayed completely unaffected in all survey years and showed no visible bleaching at any time; these patterns over time matched the regional heat stress recorded during the 2014 heat anomaly, and they also showed clear differences among species in vulnerability to bleaching.

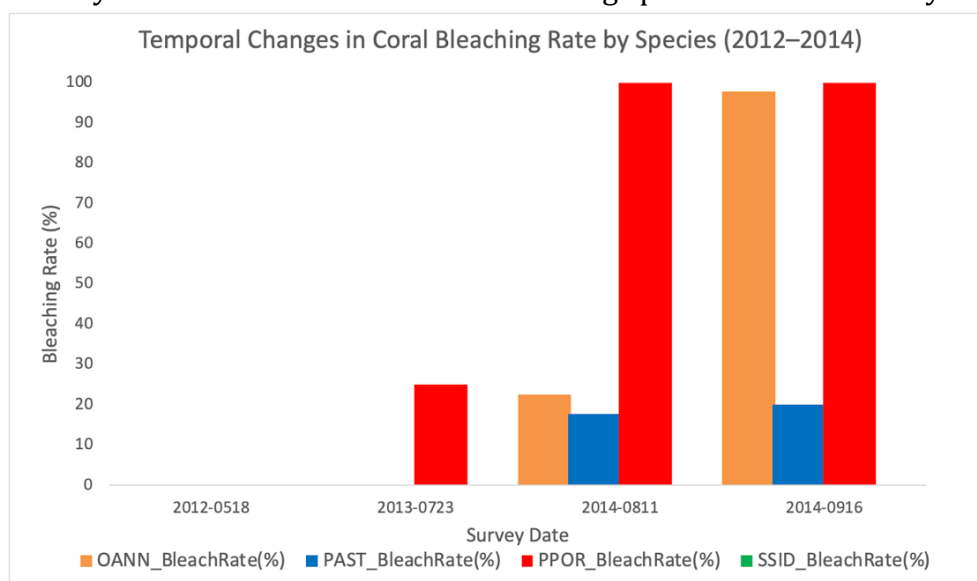


Figure 2. Changes in Coral Bleaching Rate among Species (2012–2014)

From 2012 to 2014, this figure shows how the bleaching rate changed for each coral species (OANN, PAST, PPOR, and SSID); almost no bleaching was seen in 2012 and 2013, but it went up sharply in 2014, especially in August and September; these differences among species suggest that the chance of bleaching depended on the species, with some corals responding strongly while others stayed stable.

The spatial structure patterns were assessed using the average distance to the nearest neighbor, and these patterns were different among species and across years, as shown in Figure 3; Figures 3a–3d present the patterns for each species, and OANN was the only species that showed a clear directional change that was statistically significant. Between 2012 and 2014, both OANN and PPOR had a slow increase in their average nearest-neighbor distance; this suggested that the colonies were becoming more spread out, and this may have been caused by partial death or the loss of colonies. PAST showed only small year-to-year changes, while SSID kept a very stable spatial arrangement in all three surveys. The variation within each year was large for all species, and this was reflected by the wide ranges in nearest-neighbor distances; this variation was especially large in PAST and SSID, which meant that there was a high level of spatial unevenness within each species. A single-factor ANOVA test showed that OANN had a statistically significant change in spatial arrangement between years ($p < 0.05$), but PAST and PPOR did not. These results suggested that only some species had clear changes in colony spacing during this period, and this may have happened because density changed as a result of stress.

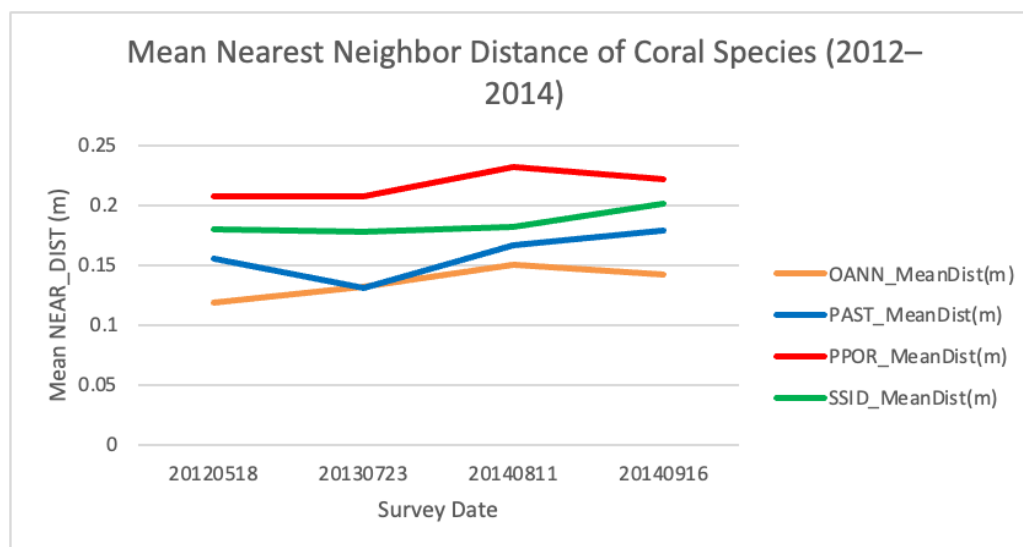


Figure 3. Changes in Mean Nearest-Neighbor Distance among Coral Species (2012–2014) Using the average nearest-neighbor distance between colonies of the same species, this figure shows how the spatial distribution of four coral species (OANN, PAST, PPOR, SSID) changed from 2012 to 2014; for some species, especially OANN, the average distance increased slowly over time; this meant that parts of the coral group became more spread out, while PAST, PPOR, and SSID showed almost no overall change in spacing; a statistically significant year-to-year increase in spacing was found for OANN (ANOVA $p < 0.05$), but no significant changes in spacing were seen for PAST, PPOR, and SSID.

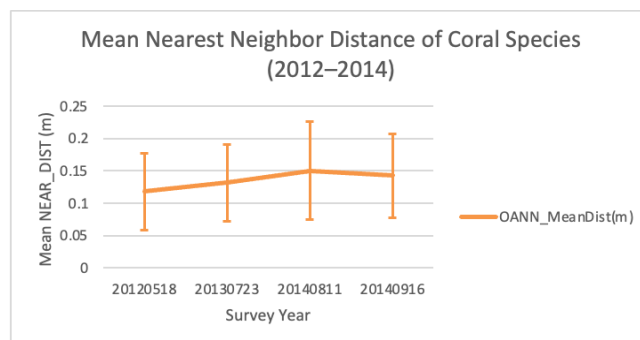


Figure 3a. OANN Mean Nearest Neighbor Distance (2012–2014)

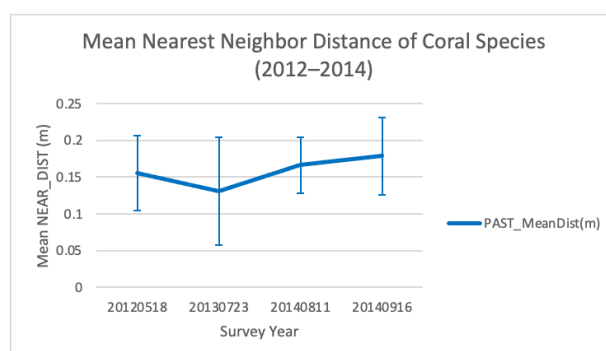


Figure 3b. PAST Mean Nearest Neighbor Distance (2012–2014)

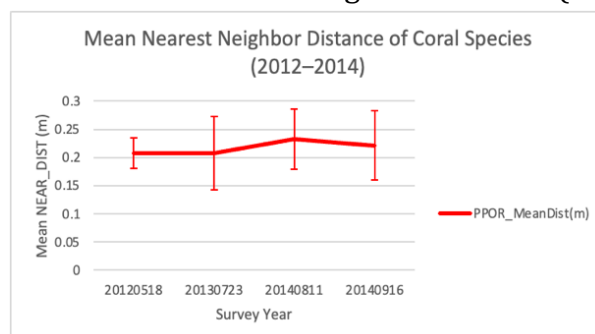


Figure 3c. PPOR Mean Nearest Neighbor Distance (2012–2014)

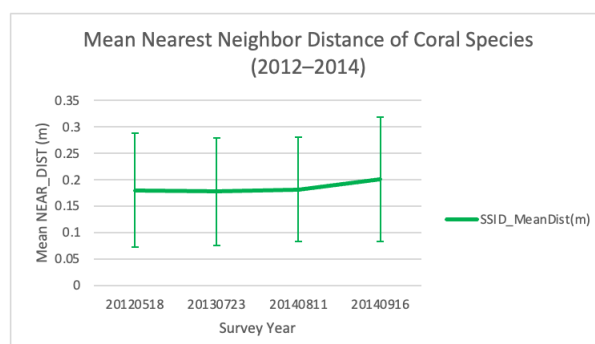


Figure 3d. SSID Mean Nearest Neighbor Distance (2012–2014)

3.2. Relationships Between Spatial Density and Bleaching Rate

The mean nearest-neighbor distance was compared with the mean bleaching rate for each species, and a general positive relationship came out: species with larger colony spacing usually had higher bleaching rates (Figure 4); the strength of this relationship changed a lot among

species, with OANN showing a strong positive connection between spacing and bleaching ($R^2 = 0.72$), PAST showing only a weak connection ($R^2 = 0.26$), and PPOR having the strongest straight-line relationship ($R^2 = 0.84$), which meant that PPOR colonies that were more spread out tended to bleach worse; SSID could not be modeled because its bleaching rate stayed at zero during the whole study. At the level of individual colonies, however, the nearest-neighbor distance was not a consistent predictor of bleaching severity; from the scatterplots of each survey year, it was seen that colonies with similar distances often showed different health results; almost no bleaching was seen at any distance in 2012 and 2013; during the 2014 heat peak, bleached and unbleached colonies often appeared at similar distances, which suggested that other factors besides how close colonies were to each other, such as local habitat conditions, colony shape, or differences in physiology, played more important roles in deciding bleaching severity; these results implied that the density of colonies alone could not explain the small-scale differences in bleaching outcomes during a major heat event.

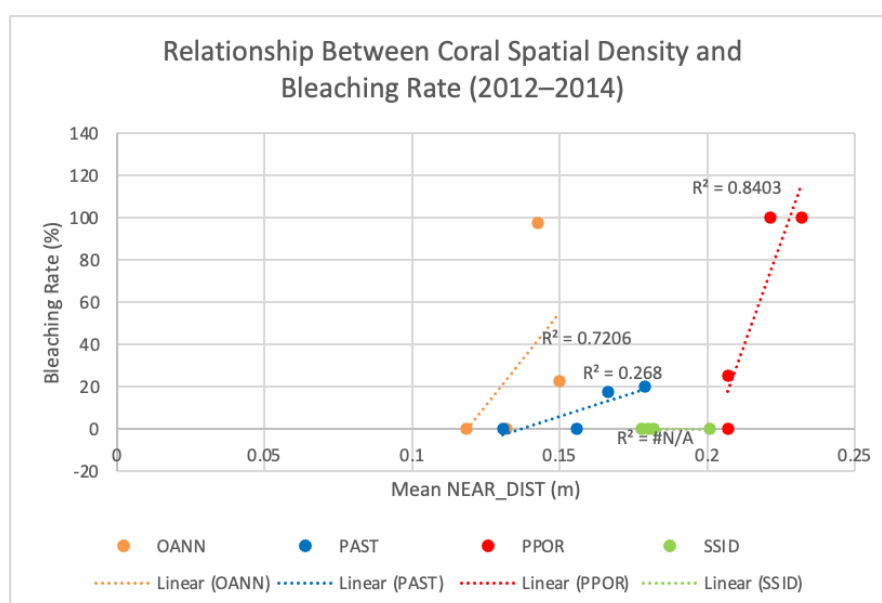


Figure 4. Relationship Between Coral Spatial Density and Bleaching Rate (2012–2014)

This figure puts together the average distance to the nearest neighbor and the bleaching rate of each species so that the relationship between them can be examined; trend lines are shown for each species, and the strongest positive associations were found for PPOR ($R^2 = 0.84$) and OANN ($R^2 = 0.72$).

3.3. Year-to-Year Patterns in Bleaching Severity and Neighbor Distance

When the link between bleaching severity and nearest-neighbor distance was checked for each single year, extra understanding was gained about how the bleaching event moved forward; in 2012, all colonies of all species stayed healthy, and the bleaching level was 0; in 2013, only a very small number of OANN, PPOR, and SSID colonies showed a little paling (bleaching level 1), and this paling generally appeared at distances greater than 0.2 m; bleaching spread quickly in August 2014, especially among OANN colonies, and the bleaching levels shown by OANN went from light paling to full color loss, while PAST and PPOR also began to bleach in this period; by September 2014, bleaching had reached its strongest point, almost all OANN colonies had lost their color completely, and PAST and PPOR showed moderate to strong whitening; SSID stayed almost completely unaffected during the whole time, and this showed a strong ability to resist at the species level; these observations from each year supported the idea that bleaching severity rose quickly and unevenly among different coral groups during the 2014 heat event.

When all colonies were pooled across species (Fig. 5e), bleaching still showed no clear spatial pattern. This additional panel confirmed that nearest-neighbor distance was not a strong predictor of bleaching severity, even during peak thermal stress.

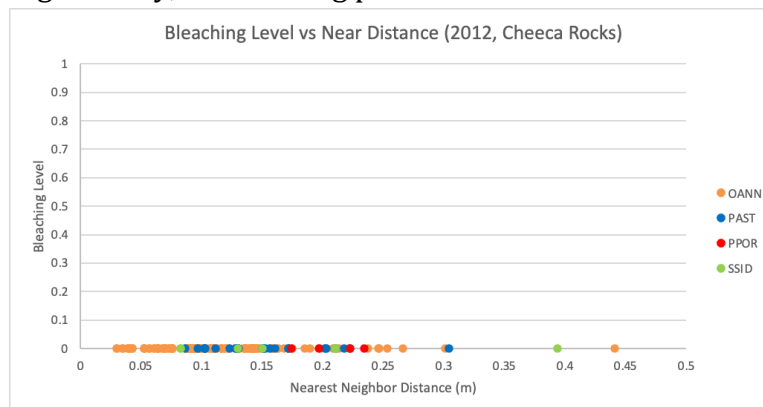


Figure 5a. Bleaching Level vs Near Distance (2012, Cheeca Rocks) Bleaching level (0–3) plotted against nearest-neighbor distance for all colonies in 2012. All individuals remained healthy (bleaching = 0).

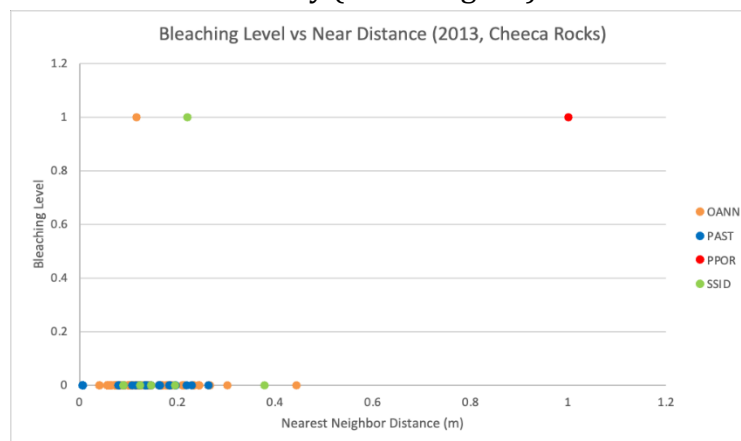


Figure 5b. Bleaching Level vs Near Distance (2013, Cheeca Rocks) A small number of colonies exhibited light paling (bleaching level = 1), but no clear relationship with nearest-neighbor distance was evident.

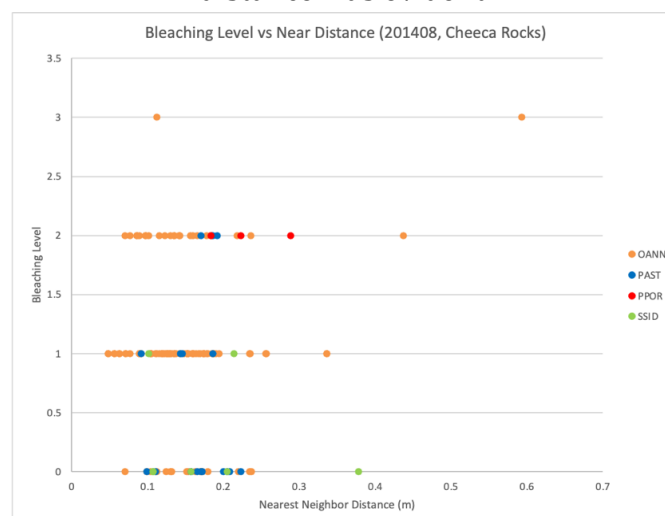


Figure 5c. Bleaching Level vs Near Distance (August 2014, Cheeca Rocks) Bleaching increased sharply across species in August 2014. Colonies with high bleaching severity (levels 2–3) appeared across a wide range of nearest-neighbor distances.

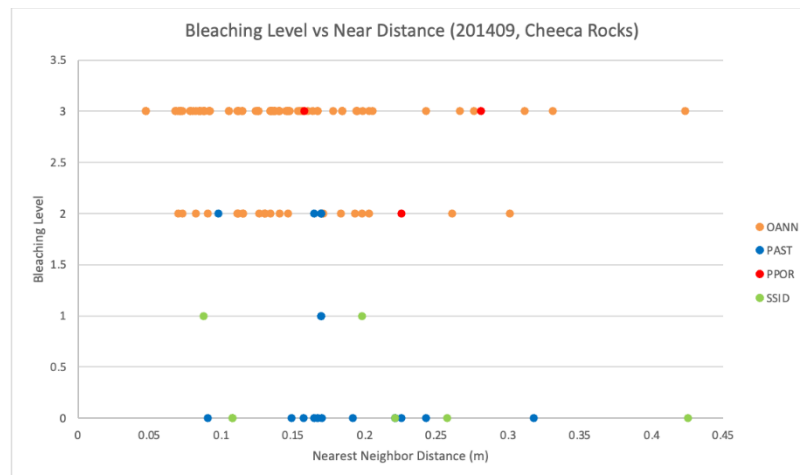


Figure 5d. Bleaching Level vs Near Distance (September 2014, Cheeca Rocks) Bleaching reached peak severity in September 2014, especially for OANN and PPOR. Bleaching severity again showed no consistent relationship with spatial proximity.

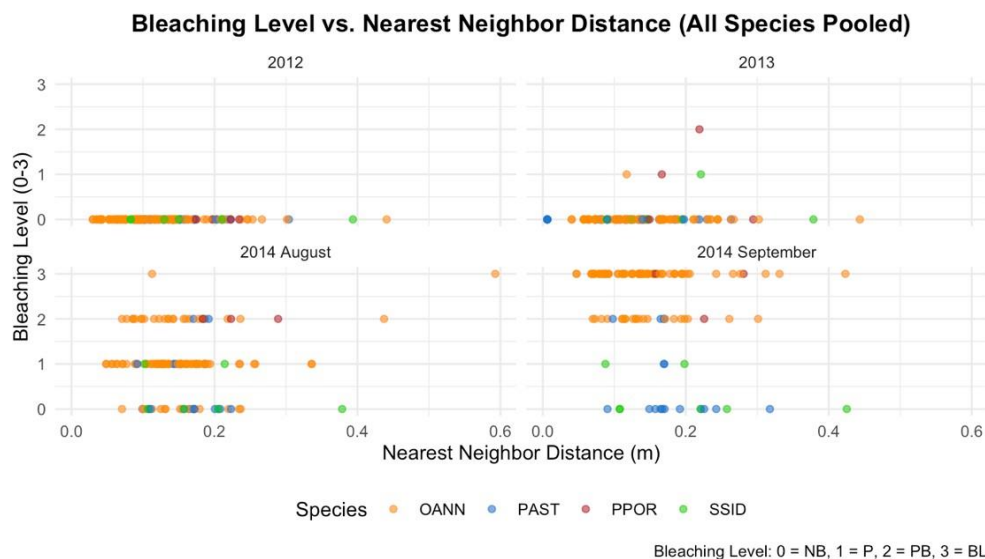


Figure 5e. Additional panel: All species pooled across all years. Bleaching Level vs. Nearest Neighbor Distance for All Species Combined (2012–2014). Pooling all colonies reinforces the conclusion that nearest-neighbor distance is not a strong predictor of bleaching severity. Even at the peak of bleaching in 2014, colonies with high bleaching and no bleaching appeared across the full range of spatial distances.

3.4. Changes in Colony-Level Spatial Distribution

More evidence for changes in colony spacing over time was provided by the boxplots of nearest-neighbor distances; in OANN and PPOR, the median distance to the closest neighbor went up steadily from 2012 to 2014, and this was consistent with the thinning of colonies in space that came from colony loss; the spacing distribution of SSID stayed stable during the whole study, and only very small change was seen in its spatial pattern; the median spacing of PAST did not change much, but there was a large amount of variation within the same year, which suggested that the arrangement of colonies within this species was very uneven; these patterns showed that spatial structure changed in different ways for different species during the study period.

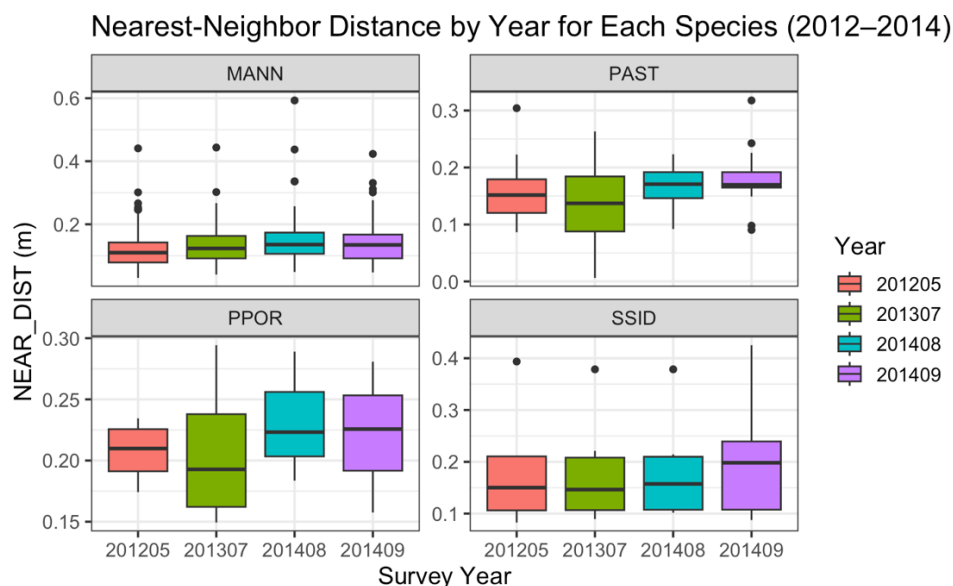


Figure 6. Boxplots showing annual distributions of nearest-neighbor distance for each species. OANN exhibits a gradual upward shift consistent with spatial thinning, while PAST, PPOR, and SSID remain relatively stable.

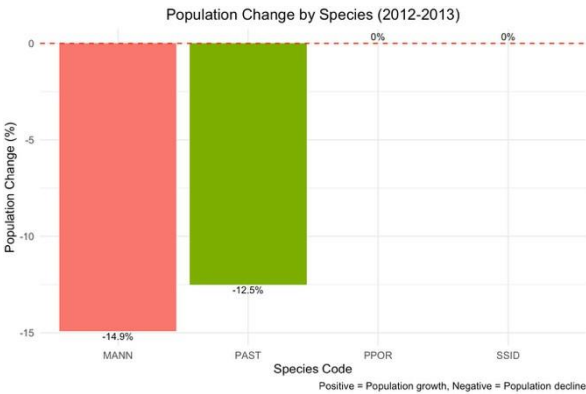
3.5. Coral Mortality Dynamics (2012–2014)

Mortality estimates obtained from colony tracking showed clear differences among species and time periods; between 2012 and 2013, moderate declines were recorded for OANN and PAST, with losses of -14.9% and -12.5% , while no detectable death was seen in PPOR and SSID; this first period came before any major bleaching, which suggested that other small-scale pressures may have helped cause these early declines.

The strongest declines happened during the 2013–2014 summer period, when the area was under a major heat event; the highest death rate was found in PPOR (-25.0%), followed by PAST (-19.0%) and OANN (-11.4%), and SSID again stayed fully resistant with 0% mortality; this sharp drop across several species marked the most severe death period of the whole study.

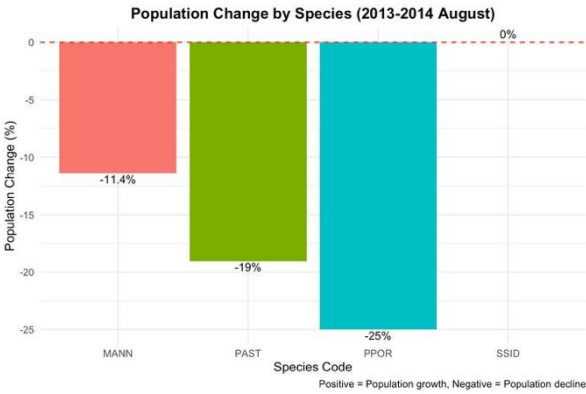
From August to September 2014, death slowed but still continued; PAST kept dropping (-17.6%), OANN had a smaller reduction (-6.9%), and PPOR and SSID both stayed unchanged at 0% ; when all periods were compared, over time OANN showed steady weakness, PAST was very sensitive during the peak heat stress, PPOR dropped sharply during the early part of the 2014 event but became stable by September, and SSID stayed consistently resistant throughout all survey years.

The 2013–2014 summer period stood out as the critical turning point when heat stress turned directly into the highest amounts of colony loss across the sensitive species.



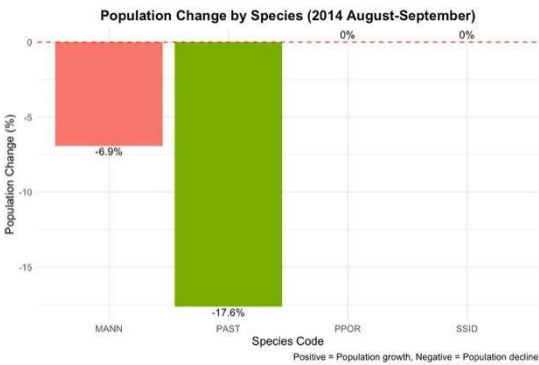
7a.

Figure 7a. Population changes by Species (2012-2013). Moderate death rates were recorded for OANN and PAST, at -14.9% and -12.5%, while PPOR and SSID kept their populations stable with 0% death; this period was the normal condition before any major stress events happened.



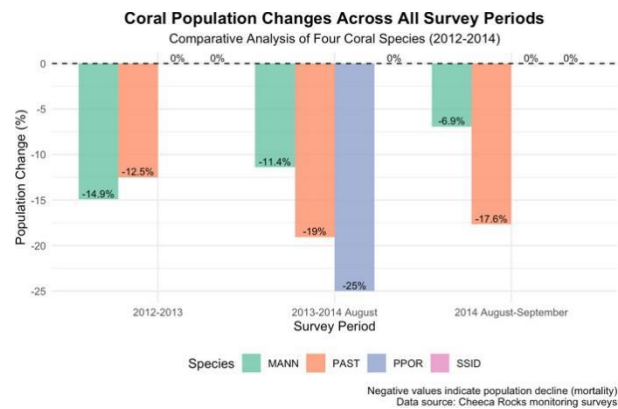
7b.

Figure 7b. Population changes by Species (2013-2014 summer period). Mortality increased sharply during this period, which aligns with documented regional thermal stress. PPOR had the strongest decline (-25.0%), followed by PAST (-19.0%) and OANN (-11.4%). SSID again showed complete resistance with 0% mortality.



7c.

Figure 7c. Population changes by Species (2014 August-September). PAST continued to show high sensitivity with a decline of -17.6%, while OANN mortality decreased to -6.9%. Both PPOR and SSID maintained stable populations. The continued decline in PAST suggests lasting or delayed impacts from earlier thermal stress.



7d.

Figure 7d. Comparative analysis of coral population changes across all survey periods (2012-2014). Populations change across time intervals for each coral species. Negative values represent mortality. The strongest declines occurred between 2013 and 2014, particularly in PAST and OANN.

4. Discussion

Colony-level photomosaic data from Cheeca Rocks were used in this study to describe changes in spatial structure, bleaching response, and mortality patterns for four coral species from 2012 to 2014; even though the 2014 bleaching event was the strongest disturbance, very clear differences among species were shown by the results, especially in how sensitive or resistant they were to heat; at the same time, the spatial changes were much more subtle; overall, it was highlighted by the findings that species identity played the major role in how corals responded to thermal stress, which was consistent with earlier work showing that bleaching sensitivity varied widely across taxa [5, 6].

Species	Bleaching 2012	Bleaching 2013	Bleaching Aug 2014	Bleaching Sep 2014	Mortality 2012–2013	Mortality 2013–2014 (Summer)	Mortality Aug–Sep 2014
OANN	0%	0%	22.55%	98%	14.90%	11.40%	6.90%
PAST	0%	0%	17.65%	20%	12.50%	19.00%	17.60%
PPOR	0%	0%	100%	100%	0%	25.00%	0%

The shift in spatial structure was one of the first patterns that was observed; from 2012 to 2014, the mean nearest-neighbor distance for *Orbicella annularis* (OANN) increased slightly but significantly, and this suggested a gradual spatial thinning of this species; background mortality, small-scale stress, or natural colony spacing processes that occurred before the major bleaching event could have been reflected by this kind of thinning; for the other three species—*Porites astreoides* (PAST), *Porites porites* (PPOR), and *Siderastrea siderea* (SSID)—obvious interannual changes in spacing were not shown, and their colony arrangements stayed mostly consistent; this partly supported Hypothesis 2, but only for OANN; these findings also agreed with Gintert et al. [3], who noted that little structural change was shown by Cheeca Rocks before 2014 at broader spatial scales; as shown in Table 2, bleaching and mortality patterns were quite

different among the four species, but the spatial structure did not shift strongly, except for OANN.

Table 2. Species-level bleaching and mortality summary for four coral taxa at Cheeca Rocks (2012–2014). Bleaching percentages represent the proportion of colonies within each species classified in bleaching categories (NB, P, PB, BL). Mortality percentages represent colony loss between consecutive survey intervals based on colony tracking.

SSID	0%	0%	0%	0%	0%	0%	0%
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The differences in bleaching among species were much stronger. OANN and PPOR showed extremely high bleaching levels in 2014, especially in September, while SSID remained completely unbleached. PAST showed moderate bleaching. These patterns strongly supported Hypothesis 1 and matched earlier work showing that coral bleaching was strongly shaped by species-level physiological traits and growth forms [5, 6]. The complete resistance of SSID also matched previous descriptions of this species as highly tolerant at Cheeca Rocks and other Caribbean sites [3].

Colony-level photomosaic data from Cheeca Rocks were used in this study to describe how four coral species changed from 2012 to 2014 in spatial structure, bleaching response, and mortality patterns; even though the 2014 bleaching event was the strongest disturbance, the results here showed very clear differences among species, especially in how sensitive or resistant they were to heat; at the same time, the spatial changes were much more subtle; overall, it was highlighted by the findings that species identity played the major role in how corals responded to thermal stress, which was consistent with earlier work showing that bleaching sensitivity varied widely across taxa [5, 6].

The shift in spatial structure was one of the first patterns observed; from 2012 to 2014, the mean nearest-neighbor distance for *Orbicella annularis* (OANN) increased slightly but significantly, suggesting a gradual spatial thinning of this species; this kind of thinning could have reflected background mortality, small-scale stress, or natural colony spacing processes that occurred before the major bleaching event; for the other three species—*Porites astreoides* (PAST), *Porites porites* (PPOR), and *Siderastrea siderea* (SSID)—spacing did not show obvious interannual changes, and their colony arrangements stayed mostly consistent; this partly supported Hypothesis 2, but only for OANN; these findings also agreed with Gintert et al. [3], who noted that Cheeca Rocks showed little structural change before 2014 at broader spatial scales; as shown in Table 2, bleaching and mortality patterns were quite different among the four species, but their spatial structure did not shift strongly, except for OANN.

Hypothesis 3 proposed that colonies closer to each other would show similar bleaching levels, but this was not supported; during 2014, colonies of all species showed bleaching across almost all distances, and healthy and severely bleached colonies were located right next to each other, while some of the widely spaced colonies also bleached; this suggested that colony spacing had very little influence under the strong thermal anomaly of 2014; this agreed with studies showing that extreme large-scale heat stress could override local spatial factors, making proximity a poor predictor of bleaching [1, 2]; therefore, nearest-neighbor distance was not a reliable indicator of bleaching outcomes here.

Mortality patterns added another dimension to species-specific vulnerability; during the 2013–2014 summer period, PAST had the highest decline, followed by OANN and PPOR, while SSID again stayed fully stable; these findings were consistent with Gintert et al. [3], who reported limited recovery and strong losses for sensitive species after the 2014 event; an interesting result was that OANN and PAST already experienced moderate declines between 2012 and 2013, even though bleaching during those years was minimal; these earlier declines may have

been related to non-thermal stressors such as sub-lethal disease, predation, sedimentation, or fine-scale habitat differences; because Gintert et al. [3] focused mainly on coral cover instead of individual colony trajectories, such early declines would not necessarily have appeared in their dataset.

The results showed that species-specific thermal tolerance (Hypothesis 1) was the dominant factor shaping community changes at Cheeca Rocks during this period; spatial structure only changed in OANN, partly supporting Hypothesis 2, and there was no strong evidence for a spatial clustering effect on bleaching, which did not support Hypothesis 3; with the addition of data from 2015–2018, future work will be able to test whether repeated heat stress or emerging diseases (such as SCTLD) generate longer-term spatial “neighborhood effects,” and whether sensitive and tolerant species follow different recovery paths; expanding the dataset to include colony area and partial mortality patterns will also help improve understanding of how coral assemblages respond to ongoing climate stress.

5. Conclusions

High-resolution photomosaic data were used to measure colony-level bleaching responses, death patterns, and changes in spatial structure for four coral taxa (OANN, PAST, PPOR, and SSID) at Cheeca Rocks between 2012 and 2014; the strongest changes in the community happened in 2014, when a regional heat event caused widespread color loss; by September 2014, nearly all OANN and PPOR colonies had bleached, PAST showed a moderate response, and SSID stayed free of bleaching in every survey year; the largest decreases in colony numbers also took place between 2013 and 2014, mostly for PAST and OANN, while PPOR decreased less and SSID showed no decrease; the change in spatial structure was smaller in comparison, with only OANN showing a clear increase over time in the average distance to its closest neighbor, while PAST, PPOR, and SSID kept stable arrangements; these results matched earlier work by Gintert et al. [3], and they gave fine-scale evidence of species-level differences in sensitivity during the 2014 heat event.

Overall, the results pointed to heat stress rather than the spatial arrangement of colonies as the main reason for bleaching and death during these years; some species did show a small amount of spatial thinning before the bleaching event, but these structural shifts were not enough to explain the strong bleaching reactions seen in 2014; instead, the built-in heat tolerance of each species strongly shaped the outcome, with SSID staying resistant the whole time, PPOR and OANN showing high sensitivity, and PAST falling between these two; these differences showed how important species identity was in shaping the community response under sharp warming; from a management perspective, species with higher heat tolerance may help keep Cheeca Rocks stable, while sensitive species will need continued attention as heat events become stronger.

Although this study only covered 2012 to 2014, the workflow built here, which included marking colonies in TagLab, aligning the layers across years, calculating nearest-neighbor distances, scoring bleaching, and estimating death at the colony level, provided a strong base for future work; adding the 2015–2018 photomosaic datasets would make it possible to examine long-term recovery, how the population rearranged after the 2014 disturbance, and the combined effects of repeated stress; including measurements of colony area and finer categories of partial death would also improve the detection of sublethal structural changes; the TagLab–ArcGIS–R process created in this project was a repeatable and expandable framework for measuring colony-level coral changes through time; with future data, this framework can support three main research paths: tracking species-specific recovery or further decline after the 2014 bleaching event, testing whether later disturbances like SCTLD create spatial “neighborhood effects” that change the risk for nearby colonies, and measuring

shifts in colony size to capture partial death and erosion. These continued analyses will be important for understanding how coral assemblages respond to rapid climate change and for guiding management decisions that support reef resilience.

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