

Long-Term Coral Reef Monitoring at Kaloko-Honokōhau National Historical Park

Key Findings and Recommendations

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1 Abstract

This report summarizes the results of a long-term coral reef monitoring program at Kaloko-Honokōhau National Historical Park. Since 2006, surveys have been conducted to track changes in coral cover, species diversity, and reef health across five key regions of the park. The findings show a statistically significant shift in coral community composition, specifically after a major bleaching event which has led to a notable reduction in coral diversity across the park. Additionally, the report examines the utility of different survey methods and shows how advanced techniques, like Structure-from-Motion (SfM) photogrammetry, can support a better understanding of long-term changes in benthic habitats.

The report provides science-based recommendations to support effective management and conservation of the coral reef ecosystems at Kaloko-Honokōhau National Historical Park. These recommendations are grounded in the findings of the long-term monitoring program and aim to enhance the park's ability to track and respond to changes in reef health. The goal of this report is to help guide decisions that improve monitoring and management strategies through a better understanding of reef condition and community change over time.

In addition to the report summary, this project provides comprehensive Rmarkdown scripts to assist NPS staff with analyzing long-term monitoring data to examine the ecological state of coral reefs within the Kaloko-Honokōhau National Historical Park.

2 Background

Coral reef ecosystems in Hawai‘i support a wide diversity of marine life, provide critical coastal protection, and hold deep cultural significance for local communities. Coral reefs within Kaloko-Honokōhau National Historical Park (NHP) are essential to the ecological integrity, cultural heritage, and marine biodiversity of the area. However, these ecosystems have faced increasing stressors over the past few decades, threatening resilience and long-term stability. Understanding how these reefs are changing over time is important to ensure effective conservation and management.

The National Park Service (NPS) established a long-term coral reef monitoring program in 2006 to track changes in reef health over time. Initially, the monitoring was conducted as a response to impending coastal developments to the north and south of the park. The program began with a digital-photo inventory of coral health, benthic cover, and algal distribution at Kohanaiki reef and near the proposed Honokōhau Harbor development. Permanent 10-meter transects were established to create a baseline dataset for long-term monitoring.

Over time, the project expanded to include 73 permanent transects that can be revisited to monitor changes in coral reef communities. This effort has produced a robust and comprehensive dataset spanning from 2006–2010 and 2017–2023, documenting shifts in benthic features such as coral, algae, and other substrate types. Building on this foundation, the monitoring program incorporated high-resolution 3D habitat mapping using Structure-from-Motion (SfM) photogrammetry to better assess changes in coral reef communities and reef structure over time. By integrating historical 2D habitat data with advanced structural complexity assessments, this program provides valuable insights into reef health, diversity, and habitat complexity. The temporal data can be analyzed to directly identify trends in coral cover, shifts in benthic composition, and assess the impacts of environmental stressors. It is important to evaluate differences in coral cover estimates obtained from the various survey methods. Evaluating the methodological variability aides in determining the most accurate approaches for long-term monitoring of coral communities.

To enhance data analysis and inform management strategies, the resource management team at Kaloko-Honokōhau NHP partnered with The MEGA Lab to assess trends in reef health and habitat structure. Findings from this collaboration provide useful insights for resource management, refining monitoring strategies, evaluating the effectiveness of existing efforts, and informing policies aimed at strengthening reef resilience in the face of ongoing environmental change.

3 Purpose and Objectives

Since 2006, the National Park Service long-term coral reef monitoring program at Kaloko-Honokōhau NHP has collected data to assess changes in reef health over time. This report highlights several key findings from the monitoring program and provides science-based recommendations to support NPS resource management. Specifically, the key objectives of the report are to:

1. Track changes in coral cover over time and across different reef locations to assess long-term trends in reef health.
2. Examine shifts in community composition and diversity over time.
3. Evaluate differences between survey methods to refine monitoring approaches and improve data comparability in future surveys.
4. Provide science-based recommendations to improve future monitoring efforts and inform marine resource management within the park.

4 Methods

4.1 Study Area

From 2006 to 2023, a total of 439 surveys were completed to assess reef condition and track ecological changes. Benthic data was collected from 73 fixed sites within five key regions of the park: Aggregate Reef, Harbor North, Harbor South, Kaloko, and Kohanaiki (Figure 1).

Aggregate Reef is a small area located just outside the Honokōhau Small Boat Harbor, bordered by boulders, a sandy channel, and a steep drop-off. The region is well-protected from swells, creating stable conditions that support coral growth. Mooring buoys and shore access make it a popular dive site, especially when rough ocean conditions limit access to other locations.

Harbor North consists of deeper sites located north of the harbor, extending approximately 420 meters along the harbor channel. The region features volcanic pavement interspersed with sand channels and rubble patches. With an average depth of 38 feet, reduced wave energy creates stable conditions that support abundant colonies of *Porites lobata* and *Porites compressa*.

Harbor South is located past Noio Point and extends southward, with transects positioned at depths ranging from 29 to 48 feet. The area is characterized by volcanic pavement, boulders, and a steep drop-off. It experiences stronger wave energy than other regions, which influences coral cover and overall habitat conditions. Due to the absence of mooring buoys and limited shore access, human activity is minimal in this area.

Kaloko is a small reef area near Kaloko Fishpond, extending approximately 100 meters with depths ranging from 19 to 39 feet. The reef consists of volcanic pavement with generally high coral cover, primarily dominated by *Porites* species, and is influenced by significant groundwater input from the fishpond.

Kohanaiki is the northernmost region surveyed within the park, located at the boundary with the Kohanaiki private club community. The reef has distinct zonation, starting with a shallow boulder zone dominated by *Pocillopora meandrina* and *Porites lobata* and transitioning to a deeper pavement zone. There is a steep dropoff around ~20 meters depth, where *Porites compressa* becomes the dominant species, forming a dense reef structure with both live and dead colonies.

4.2 Data Collection

- **2006–2010:** Data collection relied exclusively on photoquads, where high-resolution images of the benthos were taken using an Olympus T6 camera. Surveys were conducted along 10-meter transects, with images taken every meter adjacent to the transect line, covering a total area of 10 m² per plot.
- **2017–2019:** Surveys underwent a transition period, during which both traditional photoquads and SfM photogrammetry were implemented. Depending on the survey site, one of the two methods was used. This transition aimed to evaluate the feasibility of integrating SfM into long-term monitoring efforts while maintaining continuity in data collection.
- **2022–2023:** Surveys fully transitioned to SfM photogrammetry, enhancing spatial resolution and three-dimensional habitat reconstruction. Surveys were conducted using a Canon 6D camera in an Ikelite underwater housing. Images were collected across 4 × 10-meter plots, covering a total area of 40 m² per plot.

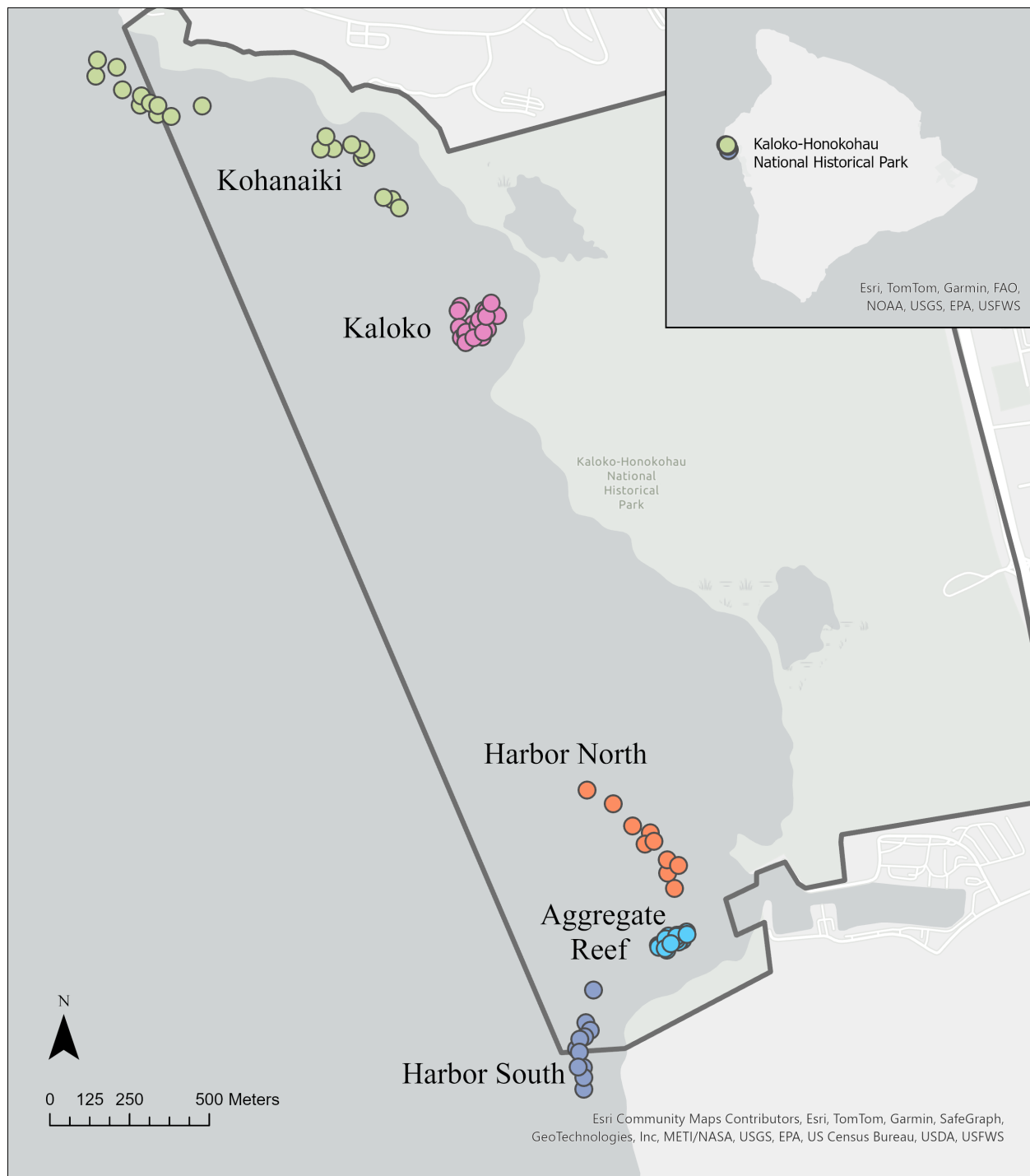


Figure 1: Location of fixed survey sites within Kaloko-Honokohau National Historical Park, colored by region.

4.3 Data Processing and Analysis

- **Photoquad** images were analyzed using Coral Point Count with Excel extensions (CPCe), applying 40 random points per frame to estimate benthic cover. A total of 400 points were analyzed per site, focusing only on areas adjacent to the transect line.
- **SfM-derived models** were built using Agisoft Metashape and annotated with CoralNet, an AI-assisted platform for automated benthic classification. A total of 1,000 random points were distributed across the entire 4×10 m survey area, with annotations taking approximately 45-60 minutes per plot. In addition to benthic classification, these models provided high-resolution 3D reconstructions for assessing habitat structural complexity. Visualizations of changes in habitat complexity during those years are provided in the Appendix (Figures 13-16).

To assess long-term coral cover trends, data from both methods were integrated, and differences in estimates between methodologies are evaluated later in this report (Objective 3). The number of surveys conducted annually varied substantially, contributing to uneven temporal coverage (Figure 2). Notably, only 2006 and 2009 included data from all five regions. These inconsistencies in spatial coverage, combined with shifts in survey methodologies over time, add complexity to data analysis and interpretation. As a result, differences in methods, site selection, and survey frequency must be carefully considered when evaluating long-term trends in coral cover and reef health.

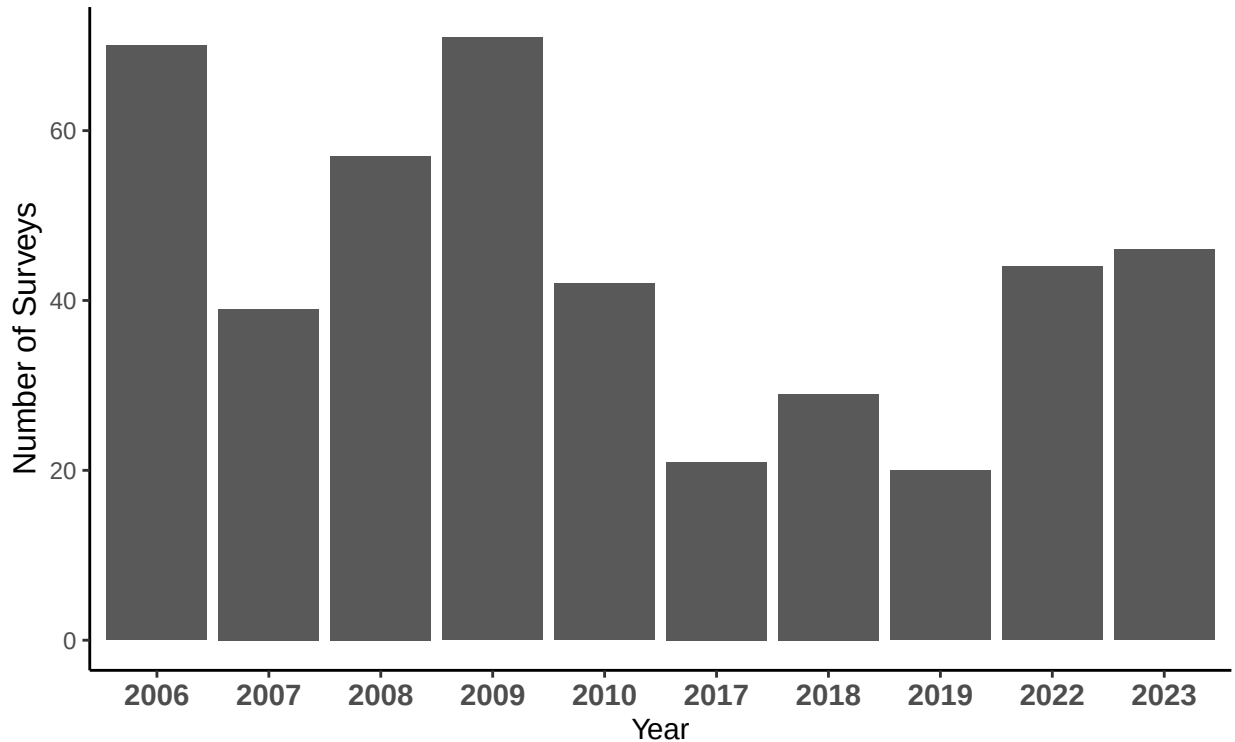


Figure 2: Total number of surveys conducted each year.

5 Results

5.1 Objective 1: Assessing Benthic Trends and Regional Variability

The most abundant substrate types across all 73 sites were turf algae and coral, with average cover values of 43.3% and 42.7%, respectively. Coral cover varied significantly across the five regions, reflecting unique environmental conditions in each area (Figure 3). Kaloko had the highest average coral cover (58.0%), significantly greater than all other regions. Harbor South (20.2%) and Kohanaiki (28.7%) had the lowest average cover, while Aggregate Reef (45.6%) and Harbor North (50.6%) had intermediate values and were not statistically different from each other. These differences can be attributed to the distinct substrate compositions of the regions, ranging from volcanic pavement and boulders to aggregate reef structures, as well as differences in exposure to wave energy. The physical characteristics of each site, including its geological features and environmental conditions, directly influence coral settlement and growth (Fujiwara et al. 2023). This results in the observed natural variation in coral cover, which supports a diverse array of benthic habitats across the five study sites.

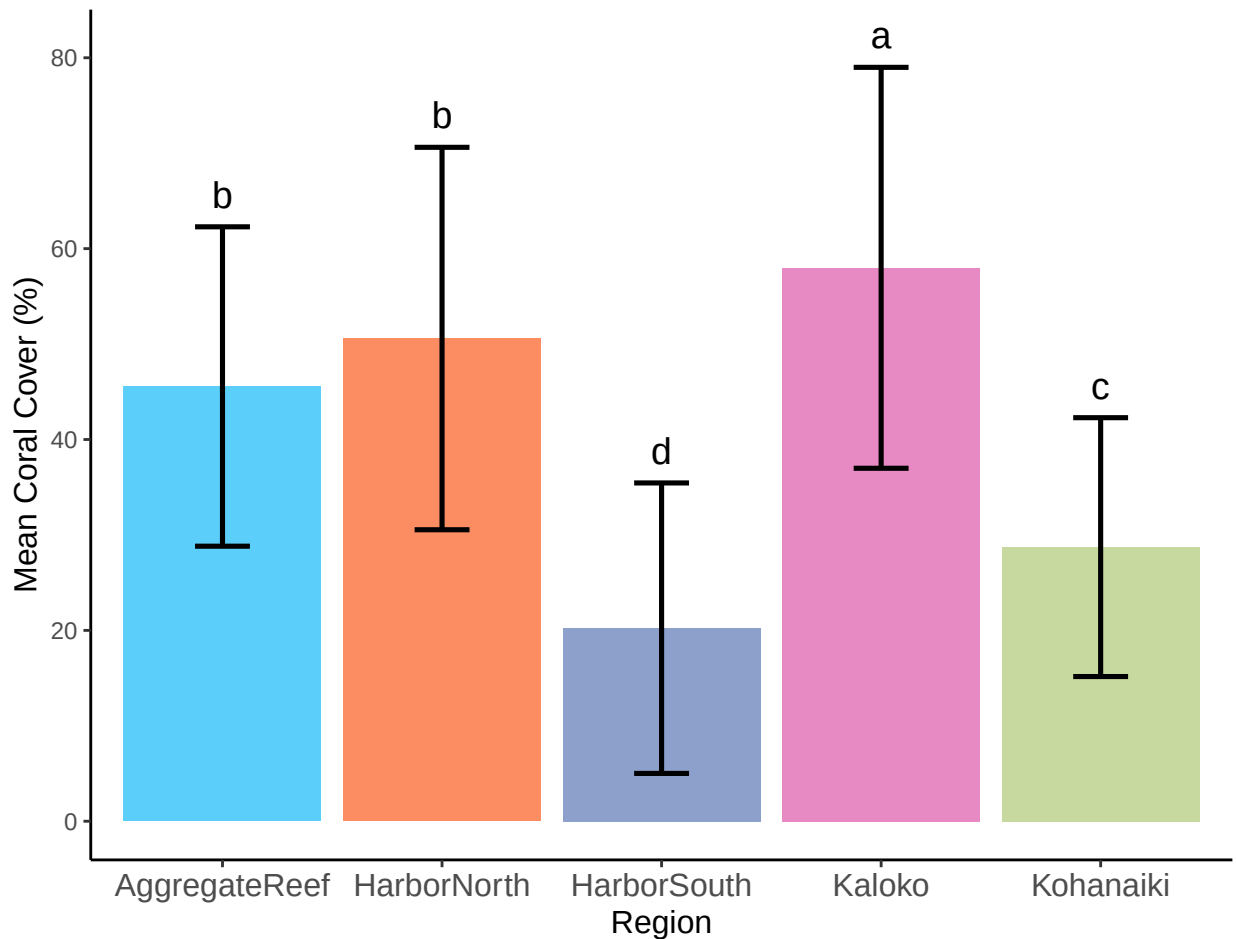


Figure 3: Mean coral cover (%) across regions (mean $\pm$ SD). Letters indicate significant differences between regions (Kruskal-Wallis, $p < 0.05$).

The analysis of percent coral cover, based on the average cover across all regions surveyed from 2006 to 2023, reveals a significant decline in coral cover after 2010 (Figure 4). The average percent coral cover decreased from 56.40% in 2010 to approximately 15.60% in 2017, reflecting a 40% reduction in mean coral cover. Several factors likely contributed to this sharp decline:

1. **2015 Mass Bleaching Event:** In 2015 there was a mass bleaching event that strongly impacted coral reefs across Hawai'i. Elevated sea temperatures caused widespread bleaching, leading to substantial coral mortality and long-term degradation of reef ecosystems. Previous studies have shown that among the National Park Service's monitored sites in the Pacific, Kaloko-Honokōhau NHP was the most severely impacted, with an estimated 77% of coral cover experiencing bleaching at its peak. This resulted in a 63% decline in coral cover between 2014 and 2016, with substantial mortality among key coral species (McCutcheon & McKenna, 2021). The substantial coral loss documented during the 2015 bleaching event likely contributed to the decline observed in this report.
2. **Method Changes:** The transition in data collection methods — from photoquads annotated using CPCE to more advanced techniques like SfM and CoralNet — may have influenced the comparability of data across years, potentially affecting coral cover estimates. New methods had greater spatial coverage and point density, increasing the accuracy of coral cover estimates (see *Objective 3*).
3. **Gap in Data from 2011–2016:** The lack of data from 2011 to 2016 limits the ability to understand how the state of the reefs changed during that period. This gap makes it difficult to pinpoint when the decline began, how severely it affected the different regions of the park, and which species were most affected during this time.
4. **Number and Location of Surveys:** The years immediately before and after the data gap (2010 and 2017) had fewer surveys conducted (Figure 2). In 2010, data was collected from only two regions, one of which was Kaloko, the region with the highest coral cover (Figure 3). In contrast, 2017 had data solely from Kohanaiki, which has significantly lower coral cover compared to other regions (Figure 3). This discrepancy in survey coverage should be considered when interpreting trends in coral cover over time. However, even when accounting for these variations, coral cover decreased from an average of 53.0% in 2006–2010 to 19.8% in 2017–2019. This represents a substantial 33.2% decrease, which is still significant even when accounting for differences in surveyed regions.

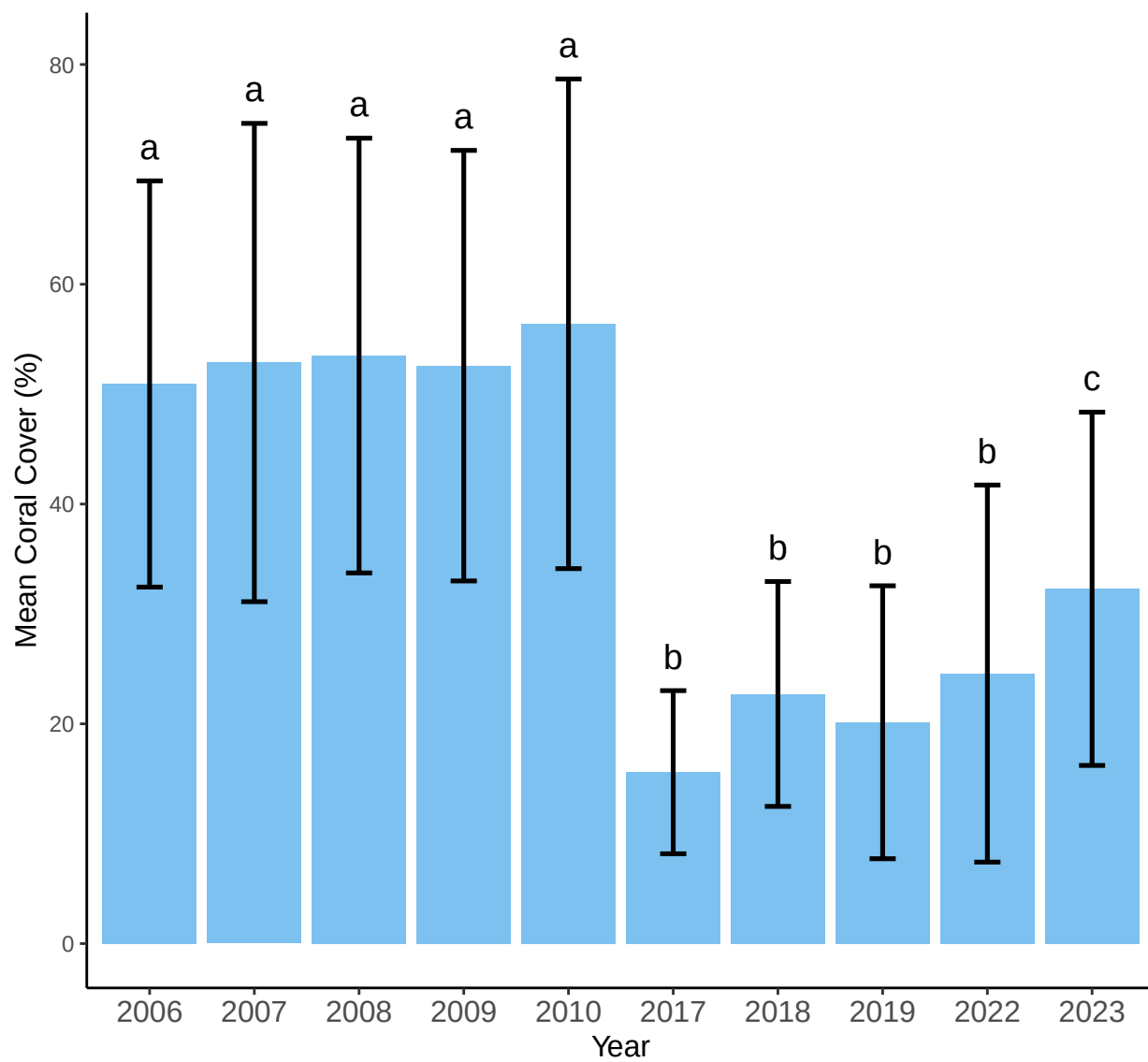


Figure 4: Mean coral cover (%) across years (mean $\pm$ SD). Letters indicate significant differences between years (Kruskal-Wallis, $p < 0.05$).

Similar changes can be observed when looking at the average coral cover over time for individual regions (Figure 5). Each region experienced the greatest decline in coral cover after 2010, with varying levels of decline or recovery thereafter (Figure 5). The strongest decline was seen in Kaloko where the average coral cover changed from 75.54% in 2010 to about 25.96% in 2018, representing a loss of almost 50% of its coral cover. Similarly, Harbor North changed from approximately 65.95% coral cover in 2009 to 25.21% in 2019, representing a loss of almost 41% of its coral cover. Interestingly, these two regions consistently showed higher coral cover compared to other regions in the park (Figure 3). Overall, these patterns highlight the sharp decline in coral cover that occurred at some point after 2010, likely influenced by a combination of environmental stressors and inconsistencies in spatial coverage and survey techniques.

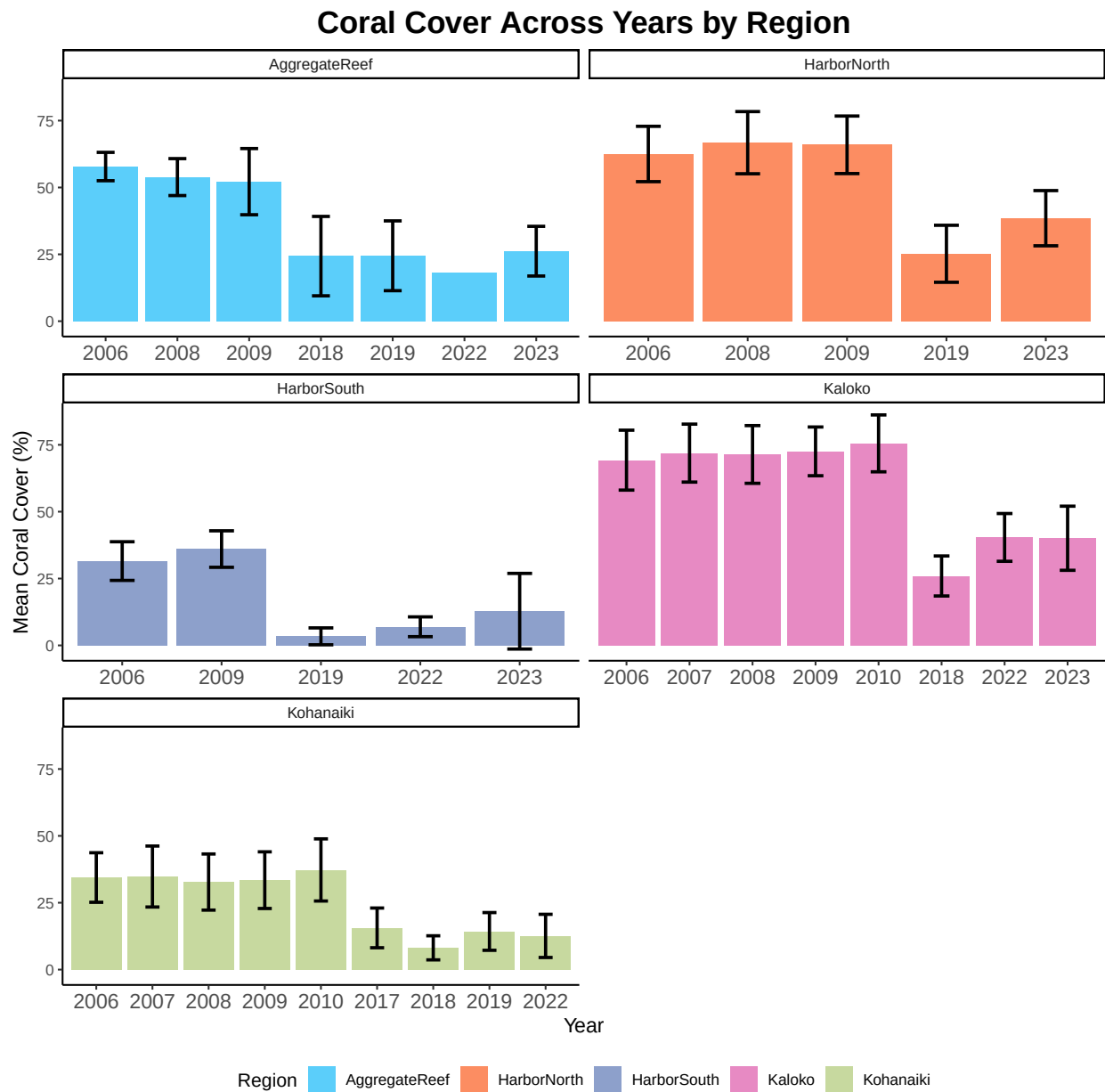


Figure 5: Mean coral cover (%) across years by region (mean $\pm$ SD).

It is important to note that inconsistencies in survey frequency and site selection introduce challenges when interpreting long-term trends. For instance, when focusing only on the SfM-derived data, which provides more accurate and precise coral cover estimates, it may appear that coral cover generally increased from 2017-2023 (Figure 6A). However, a closer look at the number and location of surveys conducted (Figure 6B) reveals that the years showing an increase also had a higher number of surveys, particularly at Kaloko—a region that consistently showed higher coral cover. This suggests that the apparent changes in coral cover may be driven more by survey distribution rather than a true biological trend. Because the park exhibits high natural variability, especially across different regions (Figure 3), long-term trends should be interpreted within individual sites or regions. Analyzing how coral cover changes over time within each long-term site offers a more accurate understanding of ecological dynamics. Ensuring consistent and even survey coverage across regions would further improve the ability to detect meaningful site-specific trends.

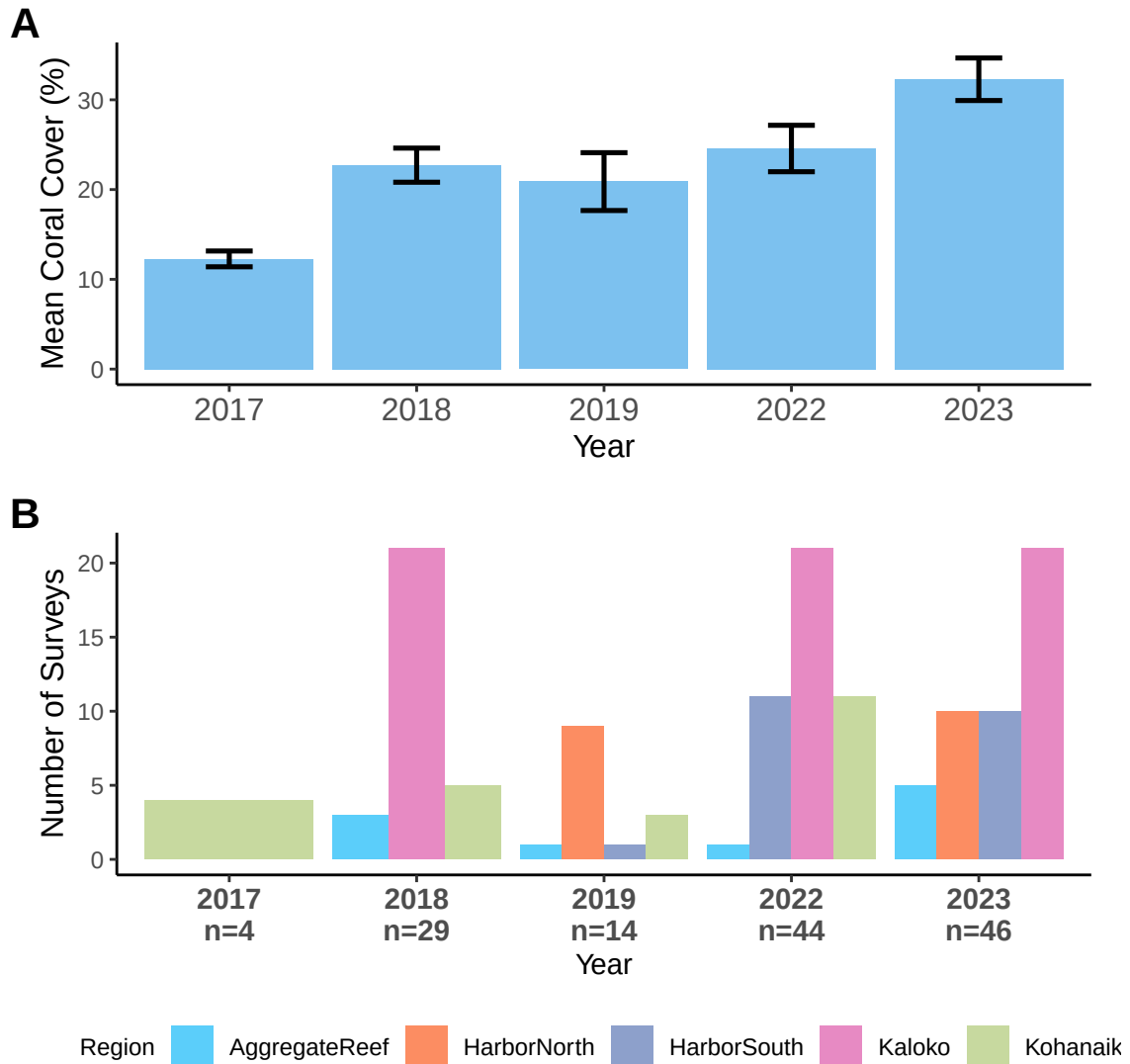


Figure 6: (A) Mean coral cover (%) across years based on SfM-derived data (mean $\pm$ SD). (B) Number of SfM surveys conducted each year by region. Bars represent the total number of surveys at each region, with total survey counts indicated below the corresponding year labels.

5.2 Objective 2: Species Composition and Species Diversity

The four most common coral species in the dataset were *Porites lobata*, *Porites compressa*, *Porites evermanni*, and *Pocillopora meandrina*. The analysis of coral species composition on the different regions shows that *P. lobata* is the dominant coral species for all regions. The average cover of *P. compressa* is highly variable, exhibiting high cover in Aggregate Reef, Harbor North, and Kaloko, but very little in Harbor South and Kohanaiki. In these latter regions, *P. meandrina* emerged as the next most abundant species after *P. lobata*. Meanwhile, *P. evermanni* remains relatively low in cover across all sites (Figure 7). These differences in species composition are likely driven by variations in environmental conditions and exposure across the regions, which in turn contribute to the creation of diverse habitats and coral communities.

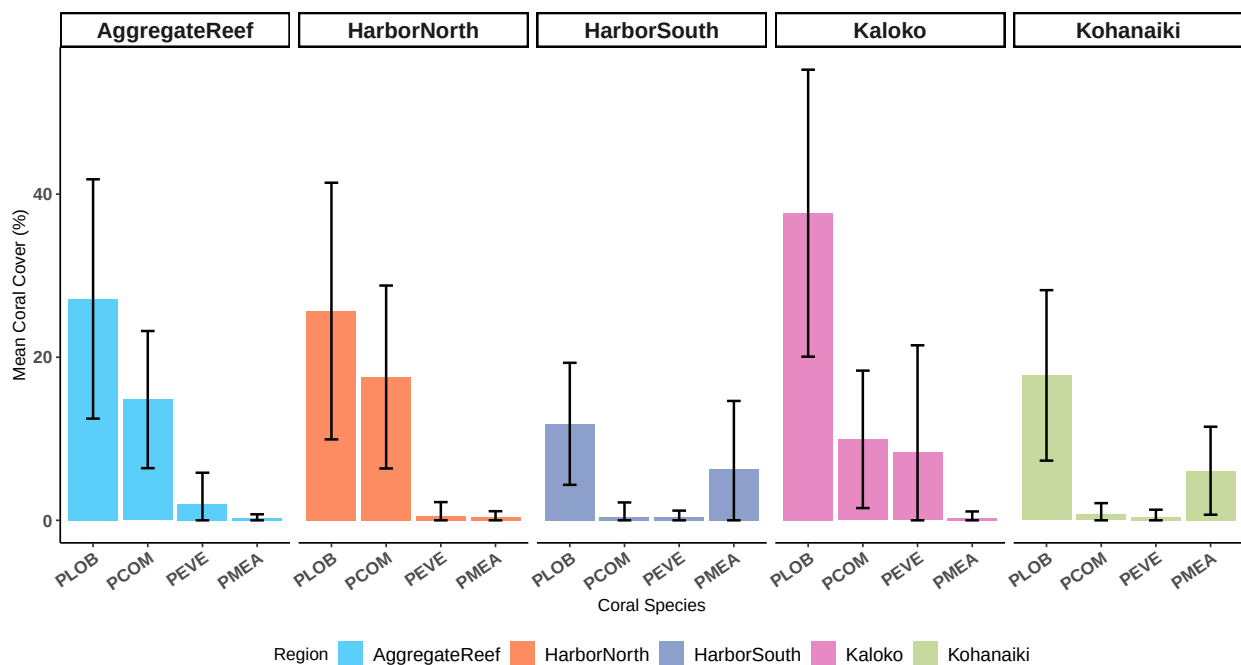


Figure 7: Mean coral cover (%) for the four most common coral species across regions (mean $\pm$ SD).

The Shannon Diversity Index was used to assess the abundance and evenness of coral species at each site. Analysis of the data reveals a notable decline in diversity after 2010 (Figure 8). From 2006 to 2010, diversity remained relatively high, fluctuating between 0.83 and 0.98. However, in 2017, when surveys resumed after a seven-year gap, diversity dropped sharply to 0.51 and remained consistently lower in subsequent years, with the lowest value recorded in 2022 (0.46). While species diversity in Hawai‘i is naturally low — typically dominated by a few *Porites* species — the sustained decline in diversity values suggests further shifts in community composition. Because the Shannon Diversity Index is particularly sensitive to the loss of even a single species in low-diversity systems, identifying which species drive these changes is critical for interpreting ecological trends and assessing the condition of coral reef communities.

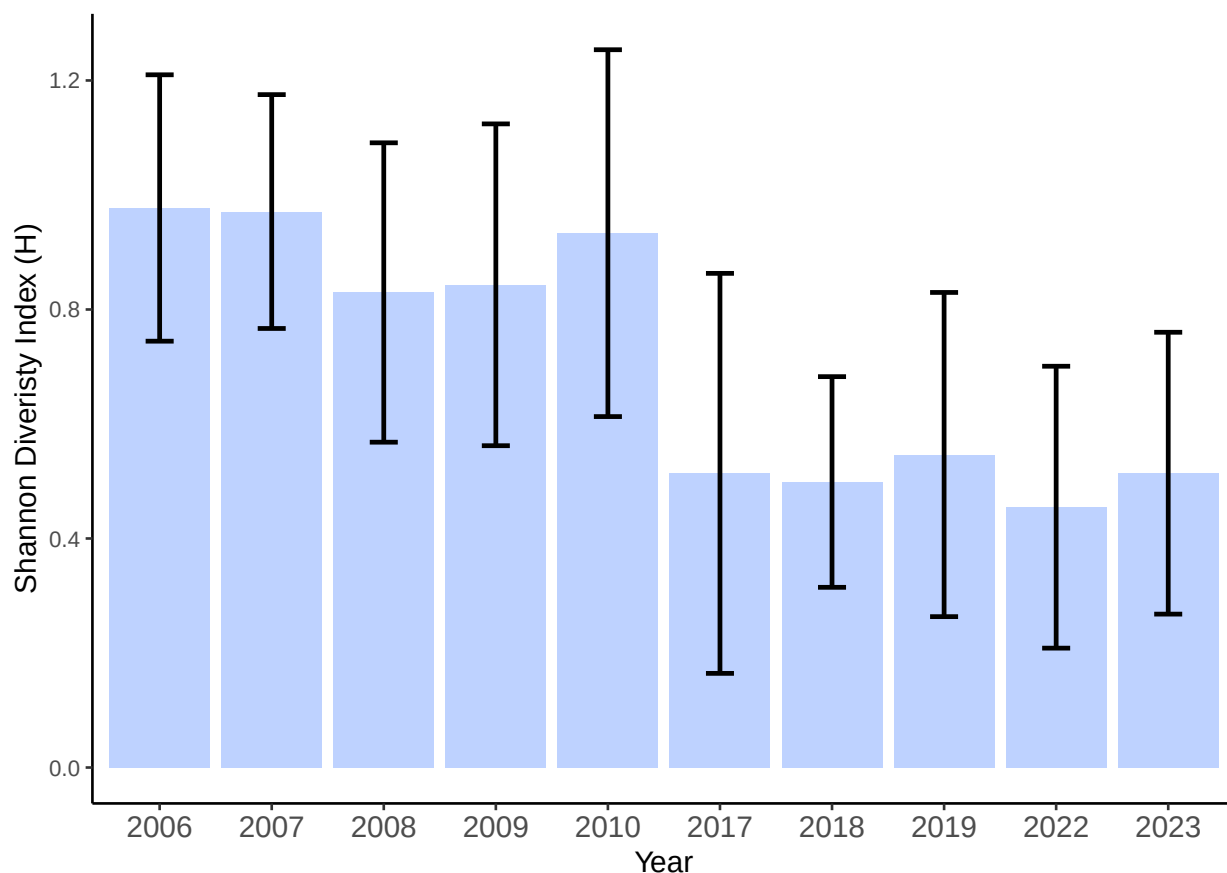


Figure 8: Shannon Diversity Index (H) across years (mean $\pm$ SD).

The observed decline in diversity can be further explained by looking at changes in the presence of specific species, particularly those that are not the dominant genera (*Porites*). There was a notable decline in coral species of the genus *Pocillopora*, primarily including *P. meandrina* and *P. grandis*. Results show a significant drop in *Pocillopora* species after 2010, with the average percent cover dropping from 4.17% during 2006-2010, to nearly 0% in subsequent years (Figure 9A). This decline can likely be attributed to the 2015 bleaching event, which had a meaningful impact on the species. Previous studies showed up to a 99% rate of bleaching of *P. meandrina* in Kaloko-Honokohau NHP (McCutcheon & McKenna, 2021), further supporting the notion that this event played a significant role in the loss of cover for this species.

Similarly, there was a significant drop in *Montipora* species, including *M. capitata*, *M. flabellata*, and *M. patula*. The average cover of these species dropped from an average of 1.22% from 2006–2017 to nearly 0% from 2018–2023 (Figure 9B). Although these species were not as abundant as the species within the genus *Porites*, their decline further contributes to the reduction in overall coral diversity, indicating a broader loss of biodiversity within the reefs.

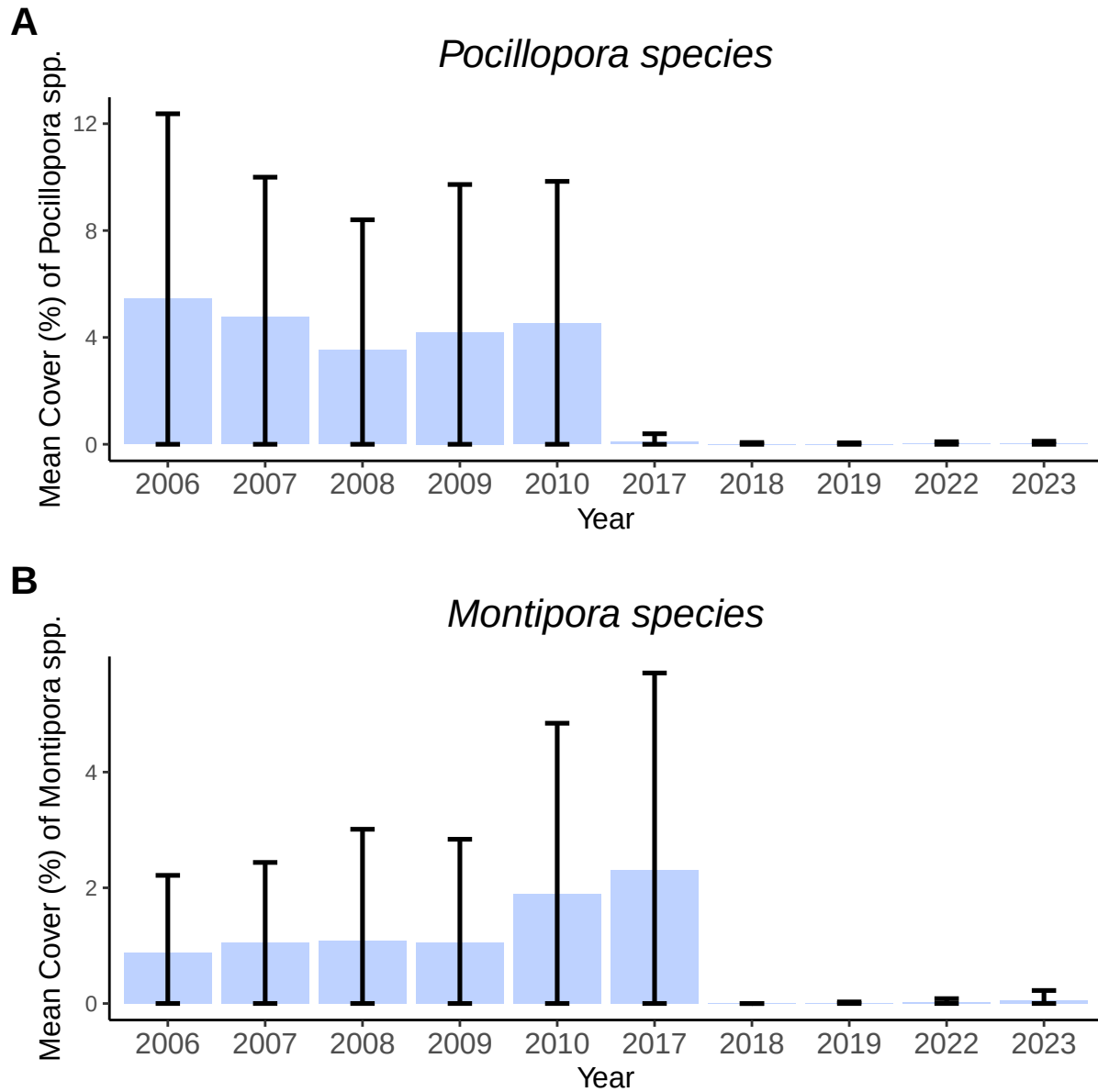


Figure 9: Mean coral cover (%) of *Pocillopora* (A) and *Montipora* (B). (mean $\pm$ SD).

To assess changes in species composition over time and evaluate community shifts, a Non-Metric Dimensional Scaling (NMDS) analysis was conducted, comparing percent cover data for each species across years (Figure 10). The ellipses represent the range of species composition in different years. Wider and more overlapping ellipses from 2006 to 2010 (shown in warm colors) suggest a more diverse and stable community, with species composition relatively consistent across years. In contrast, the narrower, more distinct ellipses from 2017 to 2023 (in cool colors) indicate a shift toward a less diverse and less stable community composition across years. The reduced overlap in recent years reflects lower similarity in species composition across years, suggesting ongoing restructuring of the community. The overall directional shift from 2006 to 2023 is further illustrated by the arrow on the plot, emphasizing the long-term trend in species change over time.

The NMDS results highlight a sustained shift in coral reef species composition over time, marked by a decline in both biodiversity and compositional stability. From 2006 to 2010, species assemblages were more diverse and stable, while from 2017 to 2023, diversity declined and community structure became more dissimilar between years. This directional shift aligns with observed declines in coral cover (Figure 4) and species richness (Figure 8), indicating gradual but persistent changes in reef community structure.

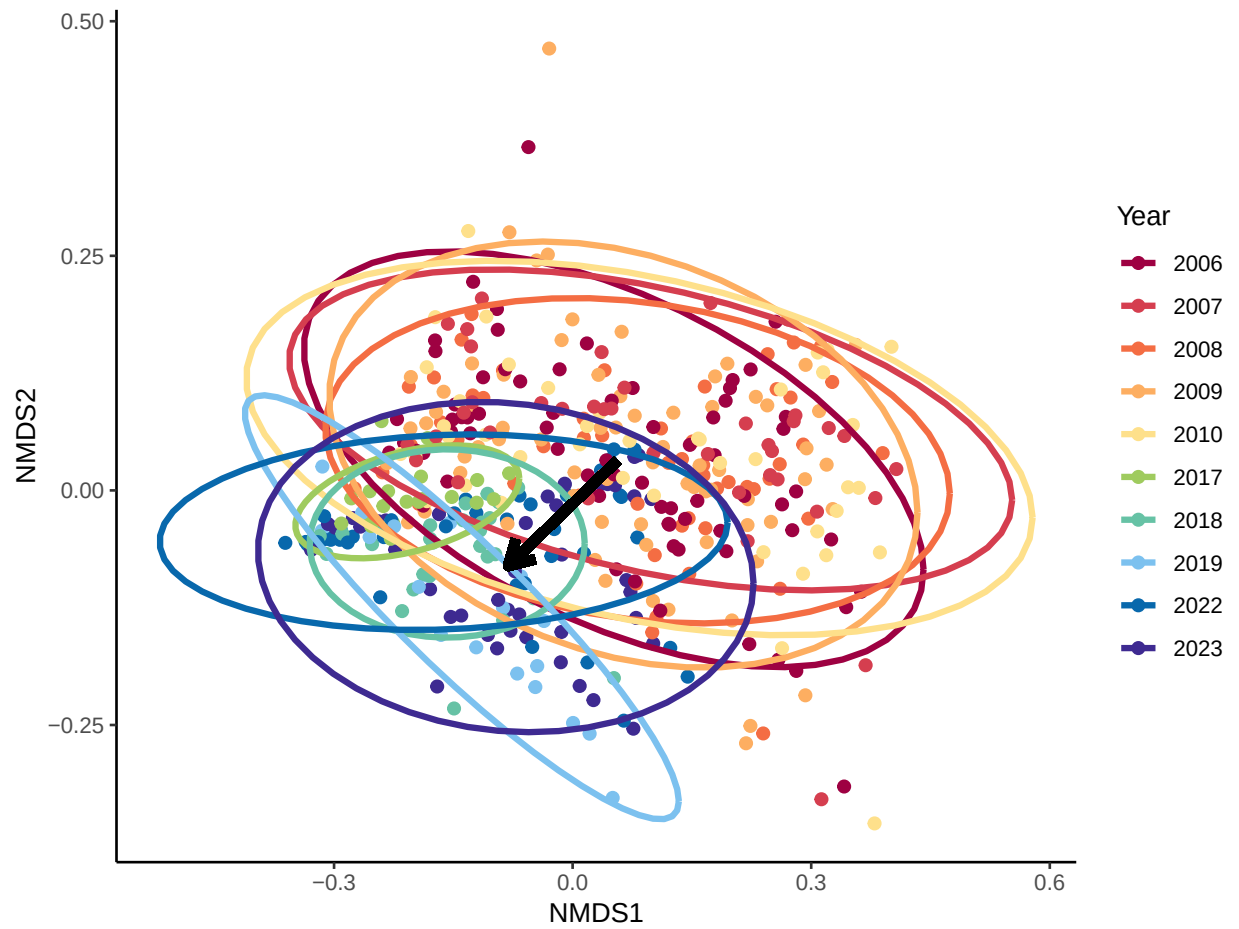


Figure 10: NMDS plot illustrating community composition by year. Points represent individual surveys colored by year, and ellipses indicate the 95% confidence intervals for each year. The directional shift in community structure over time is highlighted by the arrow, showing the transition from 2006 to 2023.

5.3 Objective 3: Methods Comparison

The analysis of percent coral cover by different methods reveals significant variations in measurement precision, as indicated by the differences in the lengths of the standard error bars (Figure 11). Photoquads and SfM quadrats exhibited the greatest variability, especially in areas with very high or very low coral cover. This increased variability is likely due to the method of annotating only 40 random points per quadrat. With fewer points, random sampling can result in a high degree of variability, as each point's classification has a greater impact on the overall measurement. This limited sampling approach may capture less representative data, particularly in quadrats with uneven or extreme coral cover.

In contrast, SfM methods using 1000 and 2000 points annotated onto the plot orthomosaic exhibited substantially lower variability across different coral cover levels, as indicated by the consistently smaller error bars (Figure 11). By increasing the number of annotated points, these methods minimize sampling error and produce more consistent measurements that are less influenced by localized variations in coral density. Furthermore, SfM techniques cover a significantly larger area of the survey plot, which improves spatial representation and enhances the accuracy of the resulting measurements. The increased sampling resolution likely provides a more accurate and comprehensive assessment of coral cover, making these SfM methods more robust for evaluating reef conditions across heterogeneous habitats.

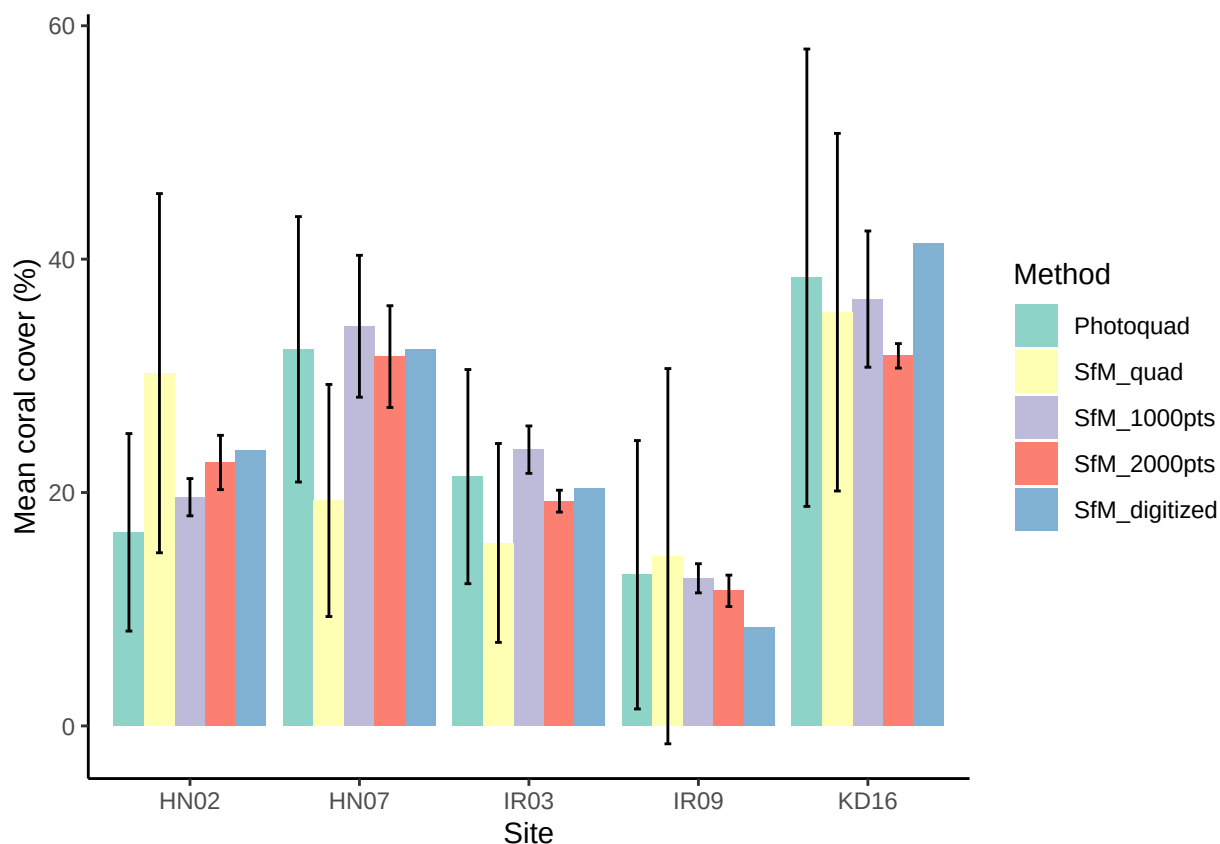


Figure 11: Mean coral cover (%) by annotation method for five selected plots (mean $\pm$ SD).

Recent analyses have been conducted to optimize annotation point density for quantifying coral

community metrics (Fukunaga et al. in review). Our results found that the most accurate and efficient estimations of coral cover and diversity are achieved by cropping each plot into 1x1 m subplots and annotating 50 random points on 50% of those subplots. Bootstrapping is then applied to the average values obtained from each subplot to estimate coral cover and diversity, reducing the influence of sampling variability while also minimizing annotation time and processing effort. For example, a 100 m² plot could achieve high accuracy and precision by annotating 50 x 1x1 m subplots with 50 annotation points each. While the 50-50 rule (50% of the survey area with 50 points in each 1x1 m subplot) is a useful guideline, we recommend testing the approach for any environment to determine the optimal combination. We are currently analyzing this for fully digitized plots at KAHO and will share the results to ensure NPS can integrate an efficient mechanism to reliably and accurately extract coral cover and diversity data.

By targeting a representative portion of each plot and applying statistical resampling, this method achieves a reliable estimate of coral cover without the need for extensive annotation, making it a practical and scalable solution for long-term monitoring in complex reef habitats. Given its balance of accuracy, efficiency, and scalability, this approach is recommended for continued use in the long-term monitoring program to ensure consistent and reliable estimates of coral cover across survey years.

6 Recommendations for Management

6.1 Survey Coverage and Frequency

Ensuring consistent survey coverage across all regions and maintaining regular survey intervals is important for detecting true biological trends, rather than patterns driven by inconsistent sampling. We recommend a minimum of three SfM plots per region to generate statistically comparable data from year to year. The park exhibits high natural variability, particularly across regions (Figure 3), so long-term trends are best interpreted within individual sites or regions, rather than relying on park-wide averages. Averaging coral cover across all regions can obscure important ecological dynamics and misrepresent local changes. Therefore, management decisions should be tailored to each individual region. To better track site-specific trends over time, each region should be surveyed with at least three sites every year to maintain spatial and temporal consistency.

The ability to conduct meaningful temporal monitoring is negatively affected if the same site is not revisited in each time point, thus it is important to aim to repeat as many sites as possible within each region. Prioritizing the sites within each region can help maintain consistency by ensuring data is collected each year from repeated survey locations. The number of sites can also be optimized based on the spatial area and variability within each region.

6.2 Data Processing

For benthic annotation, the most accurate and efficient results have been achieved by cropping each SfM plot into 1x1 m subplots and annotating 50 random points on 50% of those subplots. This method maintains the same total of 1,000 annotation points per plot as the original full-plot CoralNet approach, but distributes the effort more evenly across the entire survey area. The simple act of randomly distributing the digital 1x1 m subplots will better capture the natural variability within each survey area. Bootstrapping is then used to estimate coral cover, improving statistical

reliability while reducing annotation time. It provides a reliable and scalable method for tracking coral cover across years, particularly in complex reef environments.

An additional advantage of the SfM approach is the ability to extract 3D structural metrics that offer deeper insights into habitat complexity. These metrics complement benthic cover data and can help inform ecological assessments and management decisions. All necessary R scripts for subplot cropping, 3D metric extraction, and data analysis have been provided to support standardized and reproducible analysis.

6.3 Monitoring Options

To guide decision-making, we outline three levels of monitoring effort, each balancing accuracy and efficiency to meet different resource constraints. Time requirements were calculated by estimating approximately 20–30 minutes per survey, with an additional hour for boat transit each day, followed by one hour for model rendering at the end of each day and about one hour for annotations on CoralNet for each plot.

1. Lowest Accuracy Output (Baseline Monitoring with Minimal Effort)

- **Survey Design:** 3 SfM plots per region (15 total), each annotated with 1,000 annotation points on CoralNet.
- **Estimated Time Required:**
 - **Survey Time:** ~9 hours
 - **Data Processing:** ~16 hours
- **Software Required:** Agisoft Metashape, CoralNet (web-based platform), R Studio (statistical software)
- **Purpose:** Provides a broad, regional-scale overview of benthic cover and structural complexity trends with lower regional coverage.
- **Trade-offs:** While this approach requires less time and fewer surveys, the limited number of plots may fail to capture true patterns or ecological changes, making year-to-year comparisons significantly less reliable.
- **Best for:** Rapid assessments, long-term trend monitoring with limited resources, and preliminary site selection.

2. Moderate Accuracy Output (Balanced Effort & Resolution)

- **Survey Design:** At least 5 SfM plots per region. Each plot should be cropped in R into forty 1×1 m subplots. Then, 20 subplots will be randomly selected per plot for annotation. Each selected subplot will be annotated on CoralNet with 50 random points to assess benthic composition.
- **Estimated Time Required:**
 - **Survey Time:** ~16 hours
 - **Data Processing:** ~26 hours
- **Software Required:** Agisoft Metashape, CoralNet, R Studio

- **Purpose:** Increases spatial coverage while maintaining manageable annotation effort, offering a moderate-resolution assessment of coral cover, disease prevalence, and habitat structure.
- **Trade-offs:** While this method improves the ability to track changes over time, it still does not cover a large portion of the reef, potentially missing habitat variation and underestimating ecosystem-wide changes.
- **Best for:** Routine monitoring, detecting moderate-scale ecological changes, and informing general management actions.

3. High Accuracy Output (Comprehensive Assessment for Decision-Making)

- **Survey Design:** 10+ SfM plots per region. Each plot should be cropped in R into forty 1×1 m subplots. Then, 20 subplots will be randomly selected per plot for annotation. Each selected subplot will be annotated on CoralNet with 50 random points to assess benthic composition.
- **Estimated Time Required:**
 - **Survey Time:** ~46 hours
 - **Data Processing:** ~75 hours
- **Software Required:** Agisoft Metashape, CoralNet, R Studio
- **Purpose:** Provides high-resolution spatial and structural data, allowing for precise habitat complexity assessments, fine-scale coral health monitoring, and more robust statistical analyses.
- **Trade-offs:** While this approach maximizes data accuracy and resolution, it significantly increases survey time and annotation workload, potentially limiting the frequency of surveys or requiring automation strategies to remain feasible.
- **Best for:** Advanced ecological modeling, detailed habitat mapping and data products, and monitoring high-priority conservation zones.

Regardless of the chosen monitoring approach, the most critical priority is maintaining survey coverage across all five regions. Without consistent data collection in each region, statistical comparability over time is compromised, making it difficult to detect meaningful ecological trends or assess the effectiveness of management actions. Ensuring all regions are surveyed at regular intervals is essential for producing reliable, long-term insights into reef health and resilience.

7 Literature Cited

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McCutcheon, A. L., and S. A. McKenna. 2021. Coral bleaching, mortality, and benthic community assemblages on the reefs within the Pacific Island Network National Parks. National Park Service, Pacific Island Network Inventory and Monitoring, Hawai‘i National Park, HI.

8 Appendix

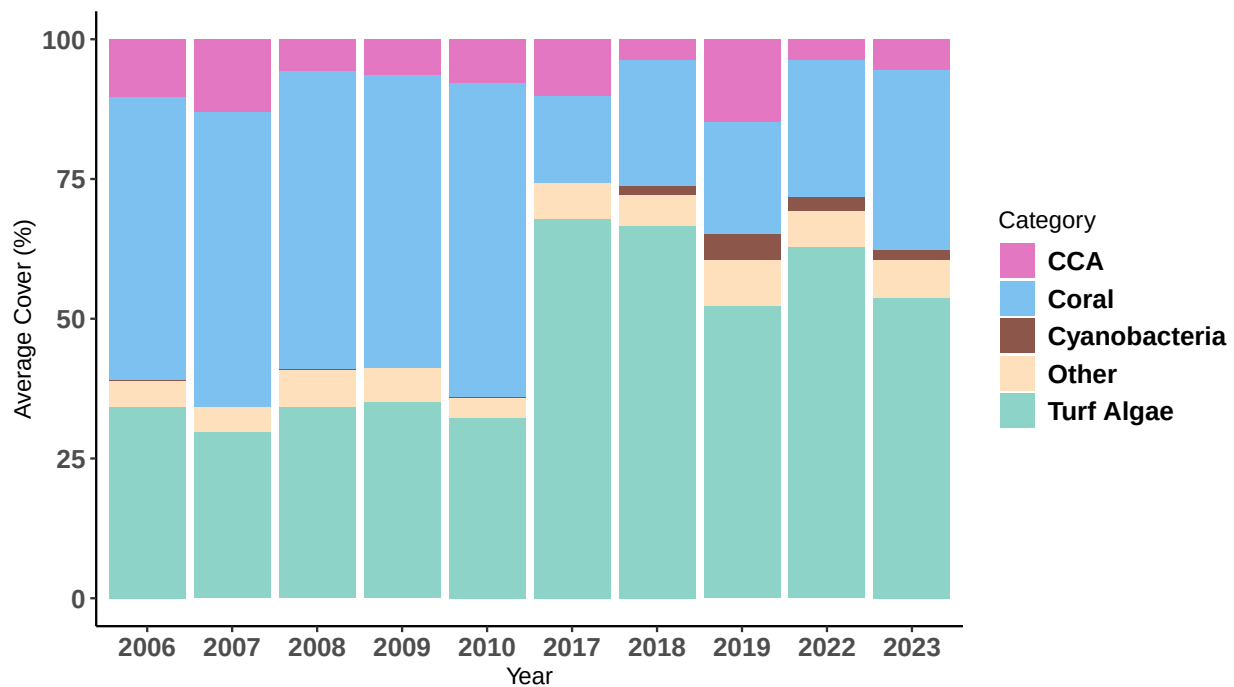


Figure 12: Stacked bar graph depicting the community composition across years. Each category represents the average percent cover.

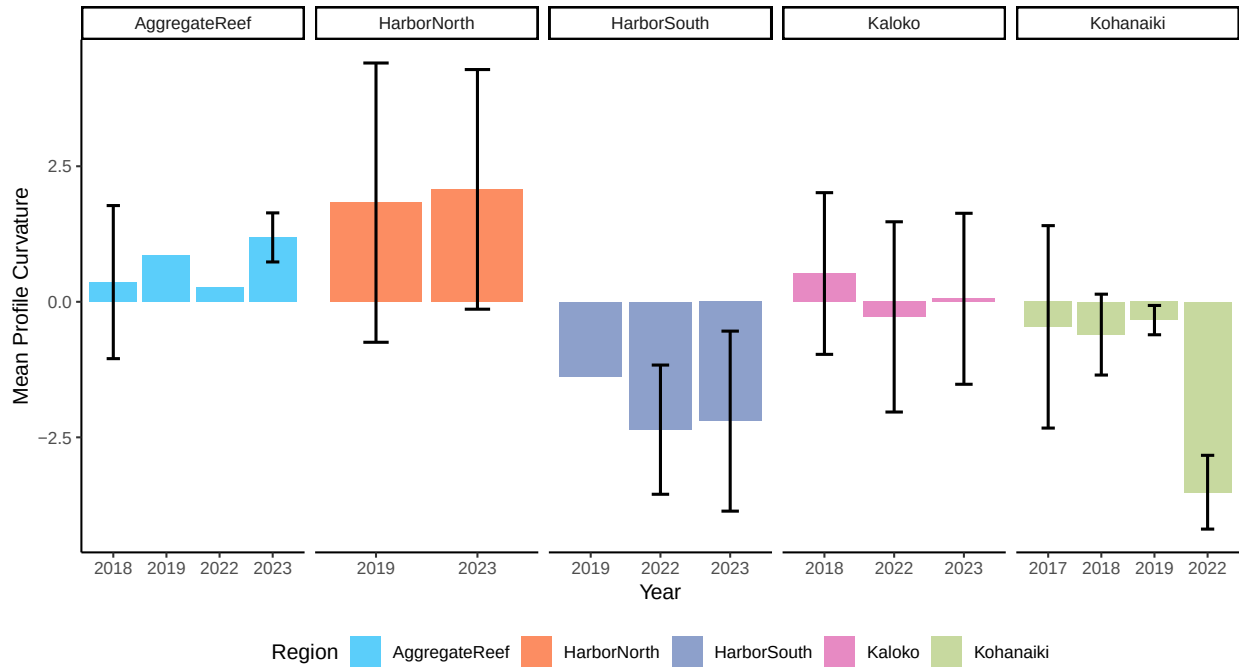


Figure 13: Mean profile curvature by region and year.

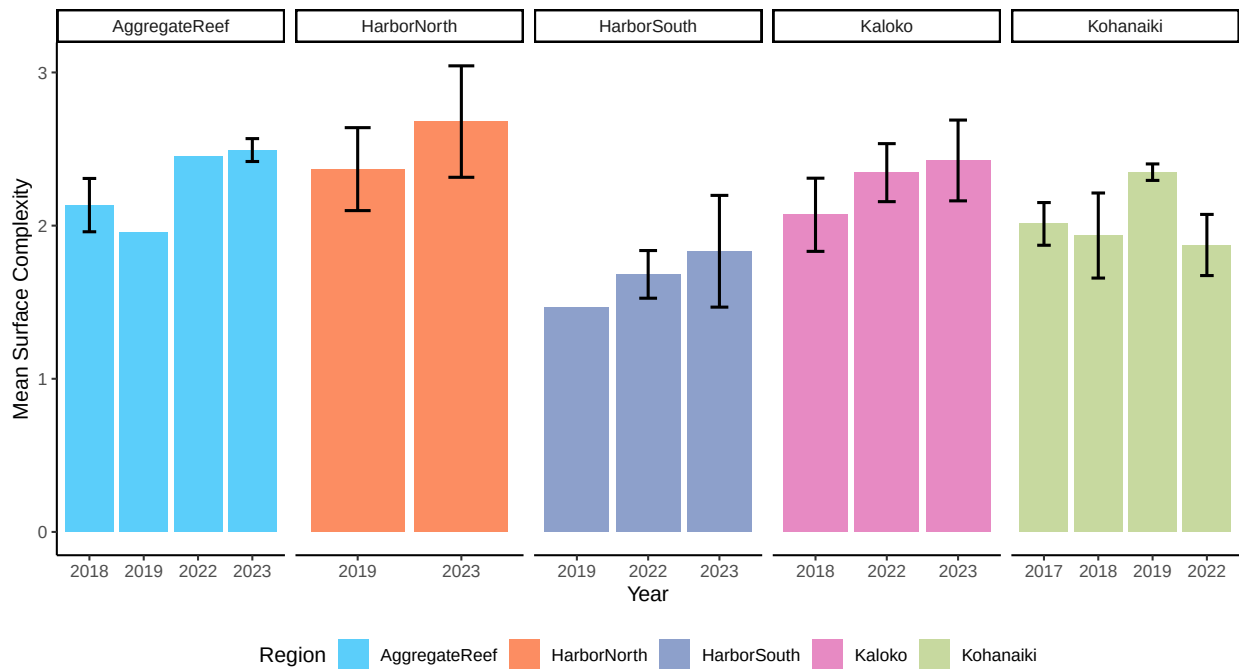


Figure 14: Mean surface complexity by region and year.

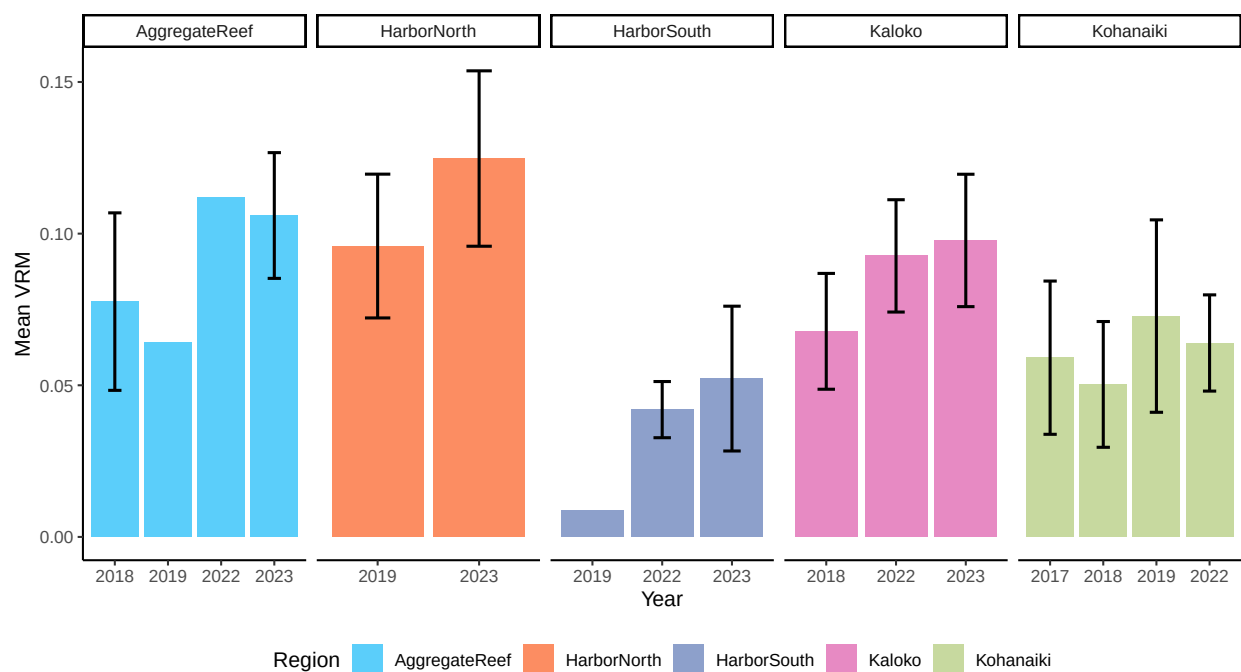


Figure 15: Mean VRM by region and year.

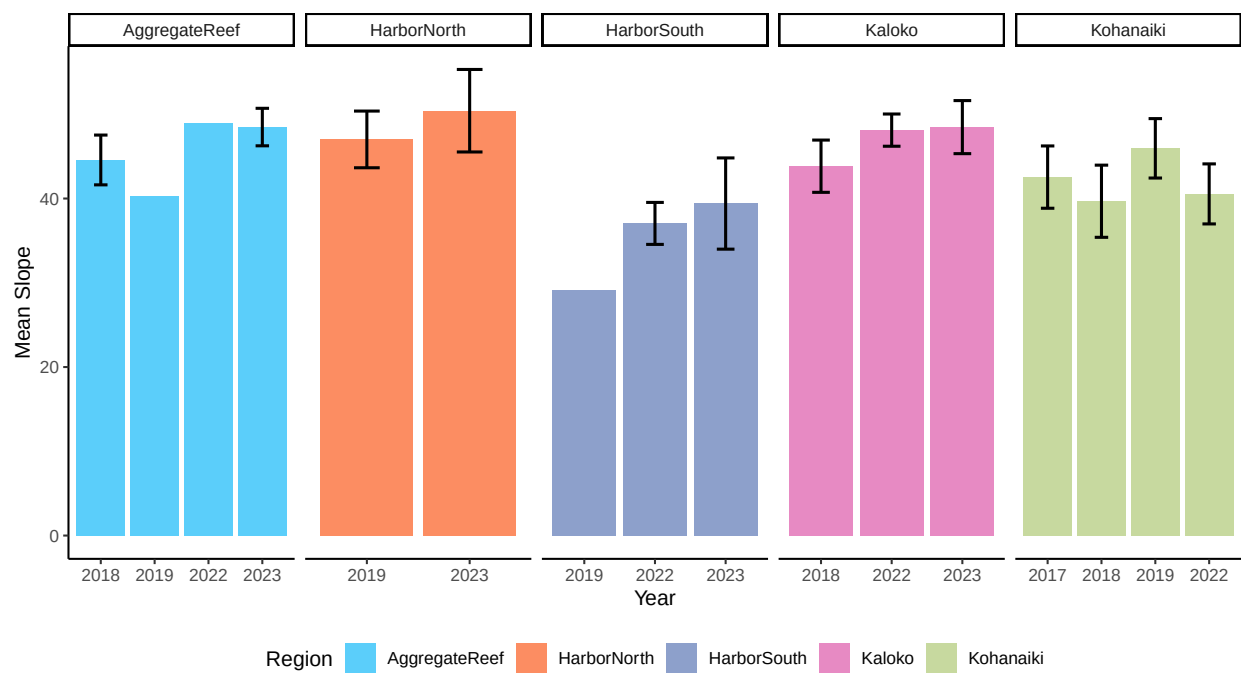


Figure 16: Mean slope by region and year.

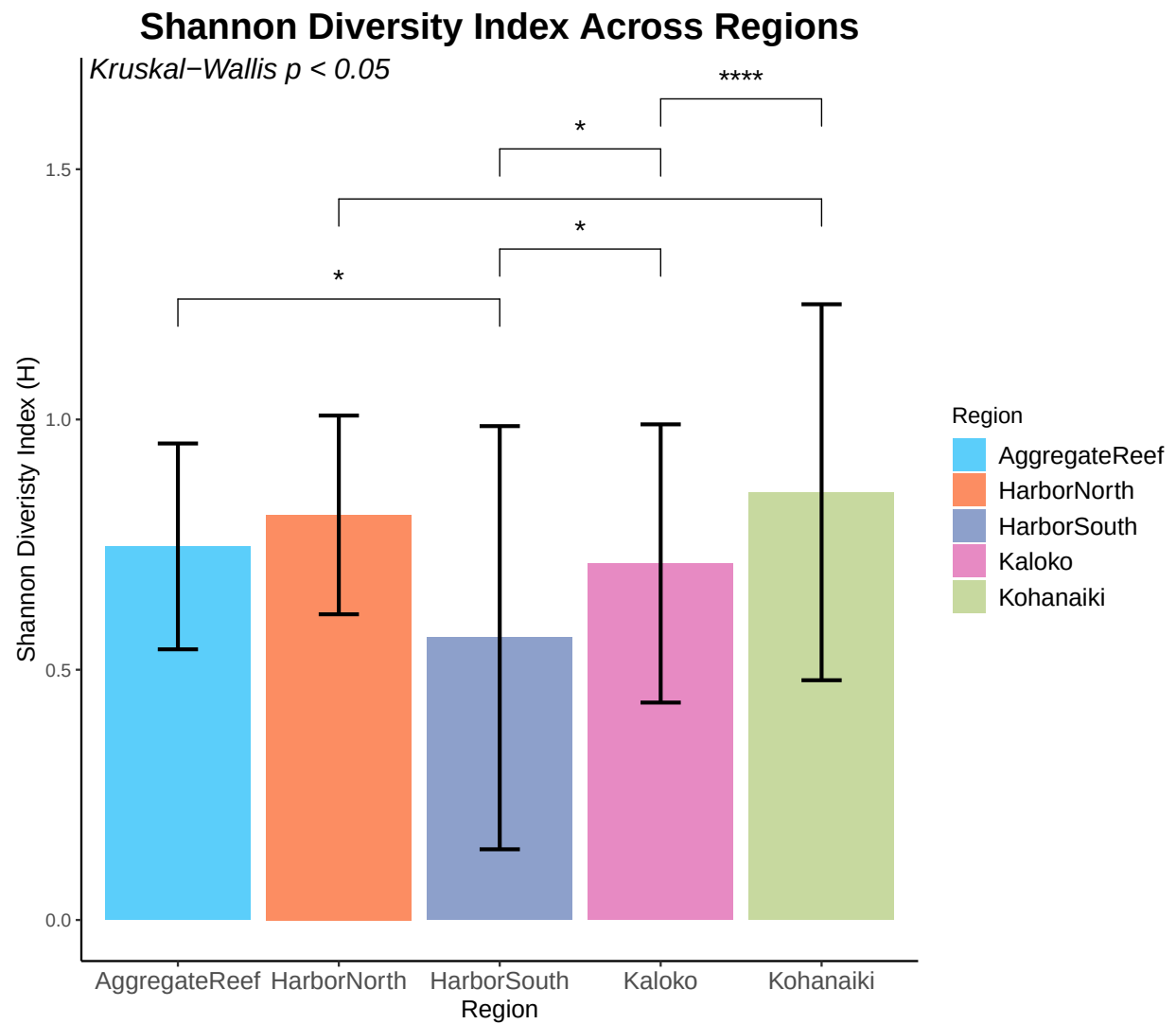


Figure 17: Shannon Diversity Index (H) across years, with asterisks indicating significant differences between regions.

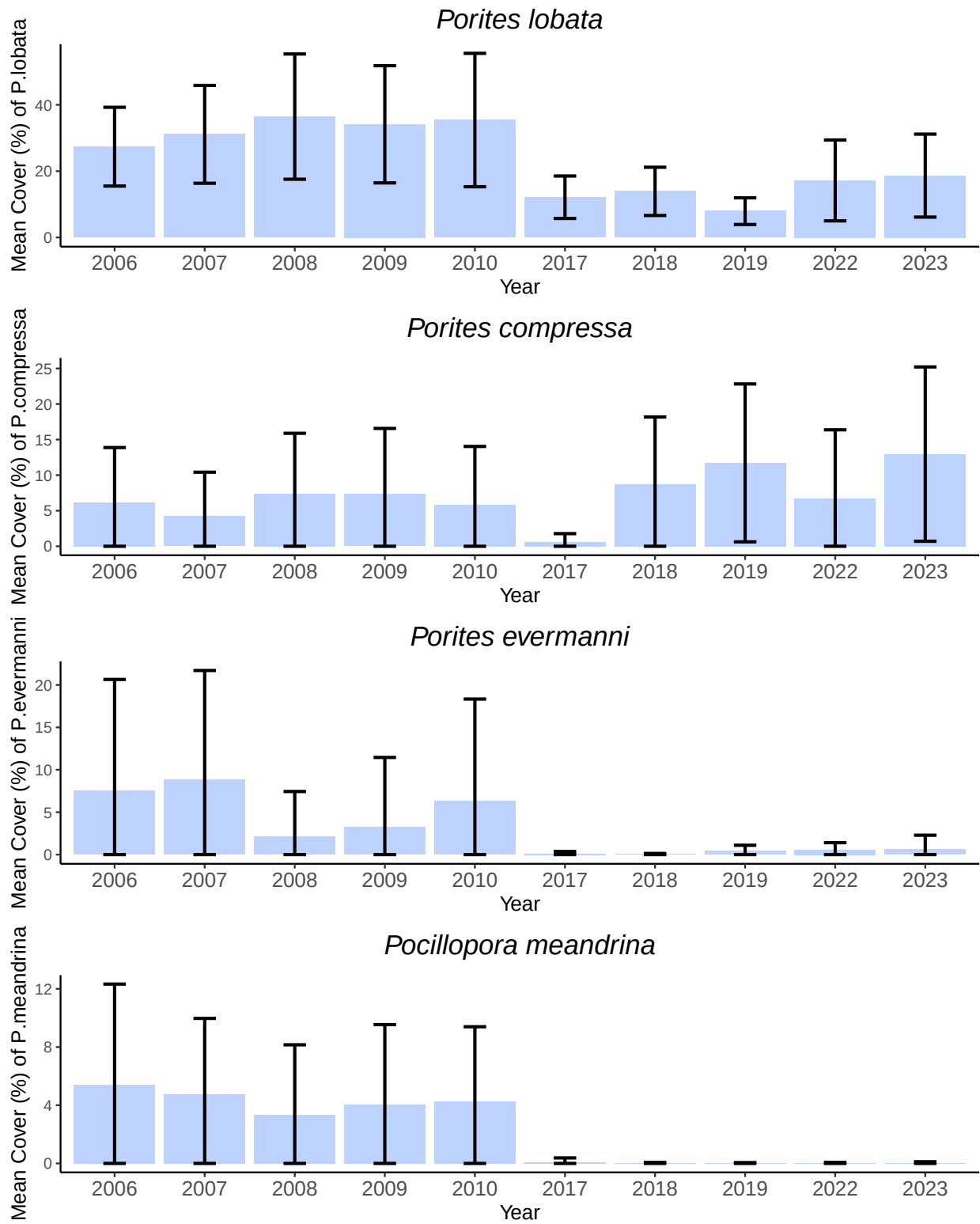


Figure 18: Mean coral cover (%) of four most common species (mean $\pm$ SD).