## Title

# Stories of Stress and Survival: Identifying Coral Bleaching Patterns to Support Reef Management in Pohnpei, Micronesia



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# Stories of Stress and Survival: Identifying Coral Bleaching Patterns to Support Reef Management in Pohnpei, Micronesia

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Capstone Project Report
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## Executive Summary

Coral bleaching, driven by warming ocean temperatures, threatens biodiversity, food security, coastal protection, and cultural identity throughout Micronesia. Pohnpei's coral reefs are experiencing an unprecedented escalation in bleaching events, with three mass bleaching events recorded in the past decade alone. These events are not part of a natural cycle but a clear signal of accelerating climate change.

In partnership with the Conservation Society of Pohnpei (CSP) and the Micronesia Coral Reef Monitoring Program (MCRM), this capstone project analyzed site-specific bleaching data from the 2024 mass bleaching event and compared it with over a decade of long-term monitoring records. The goal was to generate practical, place-based insights to support local reef management and climate adaptation.

Through spatial and species-level analysis, this project established a baseline for how Pohnpei's reefs respond to bleaching, providing a foundation for future research. It identified coral species and reef sites showing signs of resistance, explored environmental and ecological factors that may influence those patterns, and offered guidance on how these insights can support climate adaptation.

This project showed that even under intense, repeated stress, some reefs resist bleaching. Some coral communities are shifting in ways that demonstrate adaptation, and some vulnerable species persist in places we didn't expect. These patterns highlight opportunities to protect resilient reefs, refine restoration strategies, and deepen understanding of how reefs in Pohnpei are responding to climate change.

To support local application, this project produced a written summary report with findings and recommendations for CSP to use in conversations with municipal leaders, traditional chiefs, and community members. Two companion presentations, one technical and one community-facing, are being developed to further translate these findings into meaningful, action-oriented discussions.

Ultimately, this work underscores the importance of using the data we already have to guide reef conservation. By combining scientific analysis with local collaboration, it contributes to ongoing efforts to protect Pohnpei's coral reefs and the communities that rely on them.

## Introduction & Background

### What is Coral Bleaching?

Coral reefs are among the most biodiverse and valuable ecosystems on Earth, yet they are facing increasing threats from climate change. Since 1950, nearly half of the world's coral reefs have been lost, and the ecosystem services they provide, from food security and shoreline protection to cultural identity and livelihoods, are rapidly declining (Eddy et al. 2021). The reefs of Micronesia are no exception.

Because they live so close to their upper thermal tolerance limit (Reigel et al. 2009), coral reefs are particularly sensitive to rising sea temperatures. One way to understand this is by thinking about the human body: we can become seriously ill with just a slight increase in temperature, from 98.6°F to 100°F. In the same way, even a 1°C rise in ocean temperature can be extremely stressful and often deadly for corals. This narrow margin means their survival in the coming decades will depend largely on their capacity to adapt or acclimatize to warming oceans (Eddy et al. 2021). Increased frequency and severity of coral bleaching events is one of the most obvious visual signs of climate change in the marine environment.

Reef-building stony corals rely on a symbiotic relationship with a photosynthetic alga, called zooxanthellae, which provide up to 90% of their energy and give corals their vibrant color (Heron et al. 2017). Under stress, corals will expel these algae, causing their tissue to become transparent and exposing the white skeleton beneath, hence the term "coral bleaching". While bleached corals can recover if conditions improve, prolonged stress often leads to death.

The number of coral bleaching events has risen dramatically since the 1980s (Sully et al. 2019) and while localized bleaching has been recorded for over 100 years, mass bleaching events have only been observed in the last 20 years (Hughes et al. 2018). These events affect a wide range of coral species over a very large area. While local stressors may also cause bleaching, most mass bleaching events observed in recent decades have been driven by warm-water stress events across broad scales (Heron et al. 2017, Riegel et al. 2009, Sully et al. 2019). Before anthropogenic climate warming, such events were rare and less severe, allowing sufficient time for recovery between events. Now, the average interval between bleaching events is 2 to 4 times smaller and more intense, making natural recovery increasingly difficult (Hughes et al. 2018). We are seeing this story play out across the reefs of Pohnpei.

Coral Bleaching in Pohnpei: A Brief History

Pohnpei's coral reefs have historically been buffered from extreme thermal stress, but that relative stability has shifted in the past decade, with the occurrence of three major heat stress events in 2016, 2017, and 2024. Minor localized bleaching was documented on the island's northeastern barrier reef in 2004, mainly affecting *Acropora* species, although full recover was observed by 2005 (George et al. 2008). In 2010, an outbreak of crown-of-thorns starfish (COTS) caused widespread coral mortality in Pohnpei and likely contributed to increased reef vulnerability in the years that followed. This event occurred just prior to the start of formal long-term monitoring efforts supported by the Micronesia Coral Reef Monitoring Program (MCRM). Recent research confirms what many in the region already observed firsthand: COTS outbreaks and coral bleaching often go hand-in-hand (Houk et al. 2020). Both are influenced by similar environmental conditions, such as elevated sea-surface temperatures and nutrient-rich waters, which often follow El Niño events.

In 2013 and 2014, NOAA's Coral Reef Watch reported the region's first recorded instances of reaching Alert Level 1, which indicates significant thermal stress and the potential for coral bleaching. Although no formal observations of bleaching were reported during these periods, these alerts signaled the beginning of more frequent and intense thermal anomalies in the region.

Pohnpei's first island-wide mass bleaching occurred in 2016 (Figure 1), coinciding with a strong El Niño event. That year, prolonged heat stress led not only to widespread coral bleaching but also to cyanobacterial blooms (Rowley 2019). A follow-up event in 2017, though shorter in duration, compounded the damage. The most recent event, in late 2024 (Figure 1), is now the most prolonged event on record brought on by yet another El Niño event. Eastern FSM exceeded the critical 8 Degree Heating Week threshold for nearly three consecutive months, peaking at 13 DHW in October and persisting into December (NOAA CRW). For reference, a threshold of 8 DHW or higher is associated with widespread bleaching and mortality (NOAA CRW).

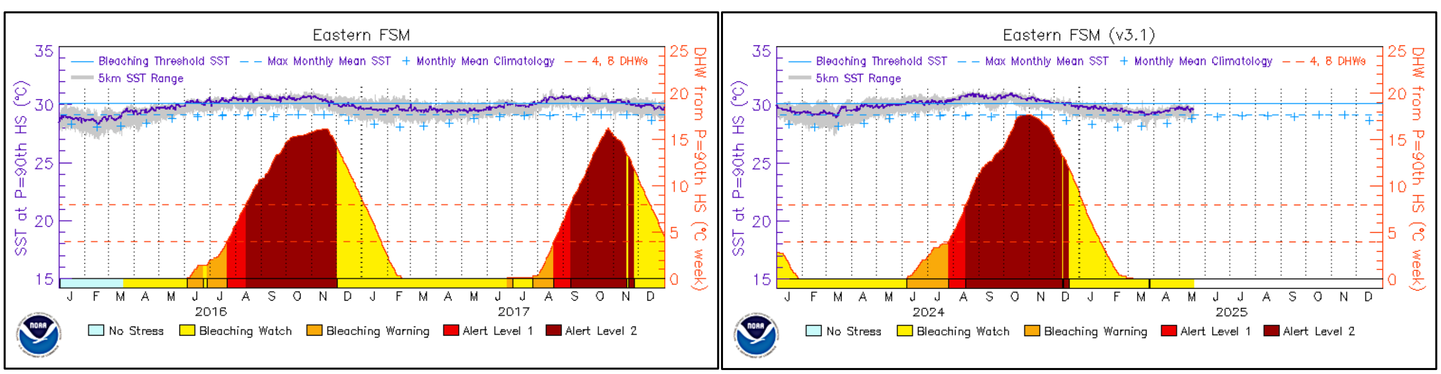
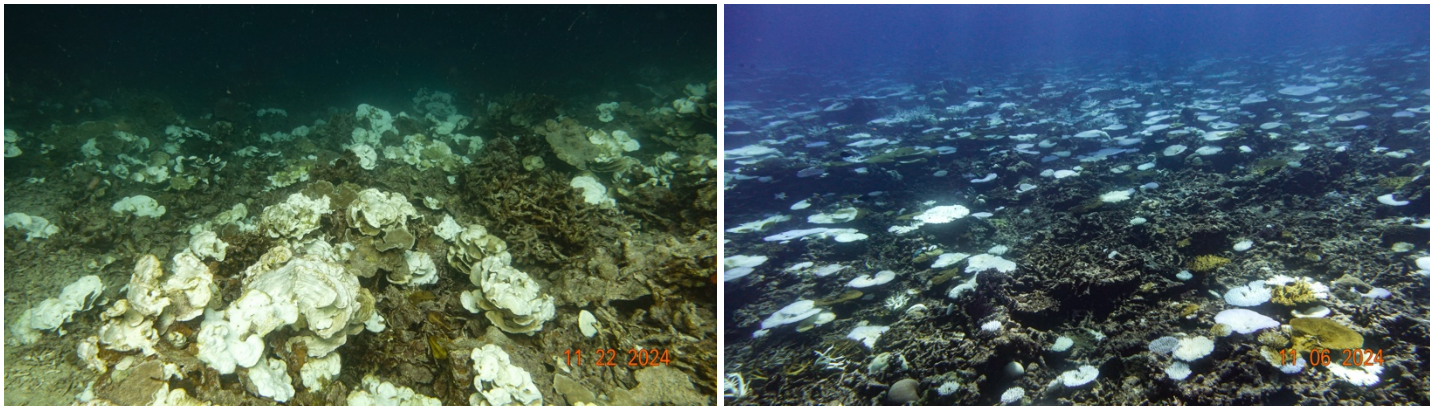



*Figure 1. NOAA Coral Reef Watch time series plots showing sea surface temperature (SST) and heat stress levels for Eastern FSM during the 2016–2017 (left) and 2024 (right) bleaching events. Colored bars represent heat stress severity based on Degree Heating Weeks (DHW): yellow (Bleaching Watch), orange (Bleaching Warning), red (Alert Level 1), and dark red (Alert Level 2). All three bleaching events exceeded Alert Level 2, indicating severe and prolonged thermal stress associated with widespread coral bleaching.*

These levels of heat stress are not part of any natural or historical cycle, this is a clear departure from the past. Just over a decade ago, Pohnpei had never recorded a single island-wide mass bleaching event. Now, these events are recurring with alarming frequency and intensity. The ocean is sending a signal: what was once rare is becoming the new reality. These reoccurring events have placed increasing pressure on Pohnpei's reef ecosystems, but they may also reveal something hopeful: not all species and sites respond the same way. Understanding how corals have responded, whether through resistance, recovery, or loss, is critical for guiding local conservation strategies in Pohnpei and across the tropical Pacific.




November 2024 bleaching event at Kipartik (left) and Madamken (right), both long-term monitoring sites in Pohnpei.

Problem Statement

The degradation of coral reefs carries far-reaching consequences not only for biodiversity but also for the communities and economies that depend on healthy reef systems. Coral reefs support an estimated 25% of all marine species despite covering less than 1% of the ocean floor, making them critical reservoirs of marine biodiversity (Knowlton et al. 2010). As reefs decline, so does the habitat for countless fish and invertebrate species, leading to cascading effects throughout the food web. This biodiversity decline has immediate implications for coastal fisheries, particularly in regions like Micronesia, where coral reef fish are a major source of food and income. As reef structures degrade, they also lose their capacity to buffer shorelines from erosion and storm surge, increasing the risk to coastal infrastructure and human safety.

These ecological changes directly undermine the ecosystem services that local management efforts aim to protect. The urgency of effective reef management has never been greater. In the face of more frequent bleaching events, managers must act with the best available data to prioritize resilient areas, support species that demonstrate resistance, and implement place-based strategies that reduce compounding local stressors. Without proactive, data-driven interventions, the cascading consequences of reef loss will continue to outpace recovery and adaptation efforts.

The Micronesia Reef Monitoring (MCRM) program has provided continuous data streams and analysis up to 2023. While local reef managers in Pohnpei collected valuable bleaching data from the 2024 event; capacity to process, analyze, and interpret this new data was limited. Without capacity to translate these long-term data streams into actionable management strategies, much of this valuable data remained underutilized. This gap in understanding the geographical and taxonomic patterns associated with repeat heat stress presents a novel challenge for effective conservation in Pohnpei and globally.

To safeguard Pohnpei's coral reefs, local managers need the ability to make informed decisions, as soon as possible. Waiting for perfect data or more advanced modeling is not always an option in the face of accelerating climate impacts. Instead, we must make the best use of the data that exists and extract insights that can guide targeted protection and management strategies.

Gaps in the Literature

Much of the existing coral bleaching research has focused on large-scale patterns of coral cover loss or the thermal stress thresholds that lead to bleaching. These studies have provided critical insights into the global trajectory of coral reef decline but often lack the taxonomic and geographic specificity needed to guide site-based management actions.

There is a limited understanding of how resistance to bleaching varies at the local scale, both across different coral taxa and among reef types. As heat stress events increase in frequency, this knowledge gap becomes increasingly urgent. Without site-level assessments of which corals or reef zones are surviving, or why, managers are left with broad vulnerability maps that may not reflect on-the-ground realities.

## Research Questions and Objectives

This project aims to support evidence-based decision-making. The goal is to provide reef managers in Pohnpei with practical tools to prioritize resilient reefs for protection, identify restoration opportunities, and better communicate climate risks and solutions to the communities that rely on these ecosystems. Working in partnership with the Conservation Society of Pohnpei (CSP) and the Micronesia Coral Reef Monitoring Program (MCRM), I analyzed coral bleaching data from the 2024 heat stress event alongside long-term monitoring datasets. This analysis focused on the following key research questions:

- What coral species or reef locations demonstrate resistance to repeat bleaching?
- What environmental and ecological factors are correlated with resistance?
- How can these patterns inform the design of climate adaptation policies?

To address these questions, I identified taxonomic and geographical patterns of bleaching severity, created visual representations of these patterns, and translated key findings into actionable insights for CSP to share across local learning networks.

Beyond these immediate objectives, this project lays the groundwork for formal analysis of potential drivers of bleaching in Pohnpei that could better inform the contemporary doctrine through eventual publication. By establishing a baseline understanding of bleaching patterns, future research can delve deeper into statistical modeling required to understand the relative contributions of multiple factors, such as temperature, water quality, and oceanographic conditions, that influence bleaching severity and recovery. This will enhance the ability to develop science-based mitigation strategies beyond Pohnpei, ensuring more effective long-term reef conservation.

## Deliverables

For this project, the primary output is a written summary report of findings and recommendations, which was developed for the Conservation Society of Pohnpei (CSP) to share with municipal leaders, traditional chiefs, and community groups. This report includes site-based observations and suggestions for how monitoring data may be used to guide local action, such as identifying resilient areas for protection or prioritizing sites for restoration.

To support future application of these findings, two presentation materials are also being developed in advance of a planned visit to Pohnpei in summer 2025. The first is a science-focused version tailored for resource managers, featuring detailed figures, maps, and summaries of key analysis results to inform climate resilience planning. The second is a simplified, community-oriented version designed for use in public meetings and outreach events, highlighting the impacts of coral bleaching and local opportunities for reef conservation.

Although these presentations are not formal deliverables of this capstone project, they will be finalized through continued collaboration with CSP to ensure the content is accessible, culturally relevant, and useful to local stakeholders. Sharing these materials in person during site visits will help translate scientific insights into meaningful, community-led management discussions and decisions.

## Project Partners

This project is supported by two key partners: the Conservation Society of Pohnpei (CSP) and the Micronesia Reef Monitoring (MCRM) Program.

The Conservation Society of Pohnpei (CSP) is the largest conservation-focused non-governmental organization in the Federated States of Micronesia. Founded in 1998 by a group of concerned citizens, CSP plays a leading role in supporting community-based management, education, and enforcement efforts across Pohnpei's Locally Managed Marine Areas (LMMAs). The organization works in close collaboration with municipal governments, traditional leaders, and state agencies to build local capacity, promote sustainable resource use, and strengthen conservation policies. Key outputs of this project will be accessible, locally relevant materials that CSP can use to inform and engage communities.

The Micronesia Coral Reef Monitoring (MCRM) Program was launched in 2010 to generate standardized data on reef health across Micronesia. By developing consistent survey protocols and partnering with scientists and institutions across the region, MCRM has built one of the most comprehensive marine resource datasets in the Pacific. This project relies on MCRM's long-term datasets to analyze coral bleaching patterns and resilience, helping to translate scientific findings into actionable guidance for local reef managers.

## Methods

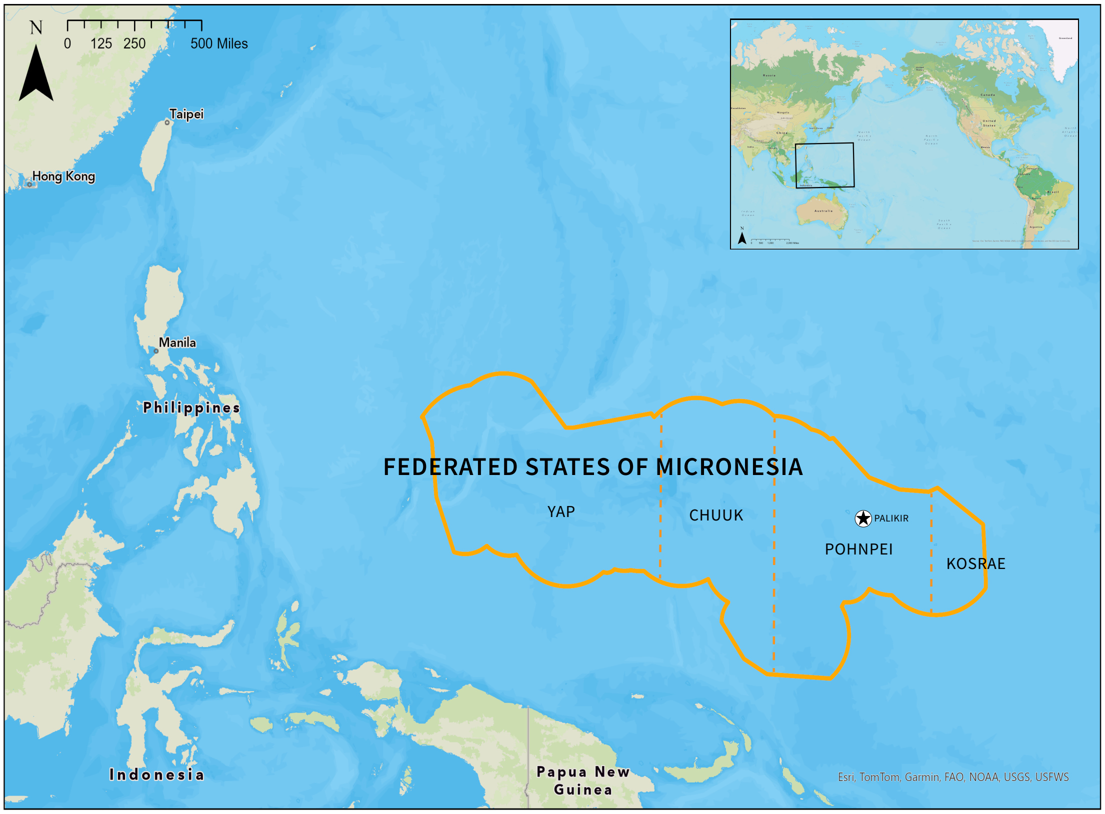
Study Area

The Federated States of Micronesia (FSM) is a sovereign island nation in the tropical western Pacific Ocean, composed of four states (Yap, Chuuk, Pohnpei, and Kosrae) stretching approximately 2,700 kilometers from east to west. These volcanic islands are characterized by rich agriculture, abundant freshwater resources, and diverse coral reef ecosystems. The nation's coral reefs exhibit high levels of species diversity and endemism (FSM NBSAP 2003), and support food security, livelihoods, and cultural identity across the region.

This study focuses on the island of Pohnpei**,** located in the north-central part of FSM. Pohnpei is the most mountainous and second most populous state, home to approximately 36,000 residents across 11 municipalities. It also hosts the national capital, Palikir. In addition to the main island, the state includes outer atolls and islands such as Nukuoro and Kapingamarangi. Pohnpei contains the greatest area of mangrove in FSM, approximately 57 $km^2$, and supports extensive seagrass meadows covering around 44 $km^2$ (FSM NBSAP 2018). This project centers on the coral reef systems surrounding the main island, which include a mosaic of habitats ranging from sheltered inner lagoons to wave-exposed outer reef slopes.

Pohnpei's reefs have experienced mounting stress over the past two decades, driven by both global and local factors. These include recurrent mass bleaching events, crown-of-thorns starfish outbreaks, and compounding local threats including overfishing, sedimentation from upland deforestation, and coastal development. Local drivers of reef degradation are strongly tied to land-based activities. More than 50 known dredging and mangrove clearing sites surround the island (TNC 2003), contributing to coastal erosion and sedimentation that smother reefs. For example, seagrass losses have also been documented due to dredging for coastal roads (FSM NBSAP 2003). Upland deforestation and infrastructure development, accelerated in part by U.S. Compact-related investments (George 2008), has led to increased runoff and pollution, particularly in estuarine zones and near river mouths. Population growth and shift from subsistence to commercial harvest over the past 30 years have also put pressure on reefs.

Pohnpei's reef systems are shaped by a highly dynamic climate and watershed system. With over 8,000 mm of annual rainfall (Rowley 2019), it is among the wettest places on Earth. Mountain-fed rivers flow through dense mangrove forests and into sediment-rich lagoons, influencing water quality and reef health. Strong El Niño events, such as the one in 2016, have triggered ecological disturbances, including cyanobacterial blooms and widespread bleaching (Rowley, 2019).




*The Federated States of Micronesia's (FSM) exclusive economic zone (EEZ) boundaries. Highlighting the four states that make up FSM (Yap, Chuuk, Pohnpei, and Kosrae) and the national capital, Palikir.*

Despite these challenges, Pohnpei remains a leader in marine conservation across Micronesia. Marine resource management in Pohnpei operates through a hybrid governance system that blends customary reef tenure with modern institutional frameworks. Traditional leaders continue to play a key role in regulating access and use of reef areas, playing a crucial role in community compliance and stewardship (OneReef 2020). These customary practices are increasingly integrated with formal management efforts led by the Pohnpei State Government and supported by community-based organizations, most notably the Conservation Society of Pohnpei (CSP).

Together, these stakeholders co-manage a network of marine protected areas (MPAs), which includes both state-designated and locally declared sites. This co-management model shares responsibilities for enforcement, monitoring, and outreach between government and local stakeholders (NFWF 2008, OneReef, 2020). Studies have found that Pohnpei's MPA system is well-managed and connected, leading to sustained increases in fish biomass (Houk et al. 2022, Isechal et al. 2014).

Pohnpei is also part of broader regional conservation efforts, including the Micronesia Challenge, which committed the FSM to conserve at least 30% of nearshore marine resources and 20% of terrestrial ecosystems by 2020. Surveys conducted across FSM found that in Pohnpei, 14% of inner and 30% of outer reefs could be considered "effectively conserved" by those standards (FSM NBSAP 2018, Houk et al. 2015).

These commitments are supported by national funding mechanisms like the Micronesia Conservation Trust (MCT), which channels sustained financing for community-based adaptation, capacity building, and protected area management. Together, these multi-scale efforts reflect a deeply rooted and evolving approach to marine conservation, one that recognizes the value of traditional knowledge, science-based planning, and shared leadership. Pohnpei is also a partner in Blue Prosperity Micronesia, a collaboration with the Waitt Institute and other stakeholders to support marine spatial planning, sustainable fisheries, and the strategic expansion of MPAs. This initiative reinforces the island's commitment to science-based, community-driven ocean governance and provides a platform for long-term conservation planning that is inclusive of traditional knowledge, modern science, and policy innovation.

Survey Design and Data Collection

The Conservation Society of Pohnpei and Pohnpei State Fisheries are responsible for coral-reef monitoring activities and have the authority to conduct this research. Given the non-invasive nature of this research, no permits were required. Survey sites were selected based on established long-term monitoring locations with existing baseline data. Site selection spans multiple reef types and regions of the island to capture spatial variability.

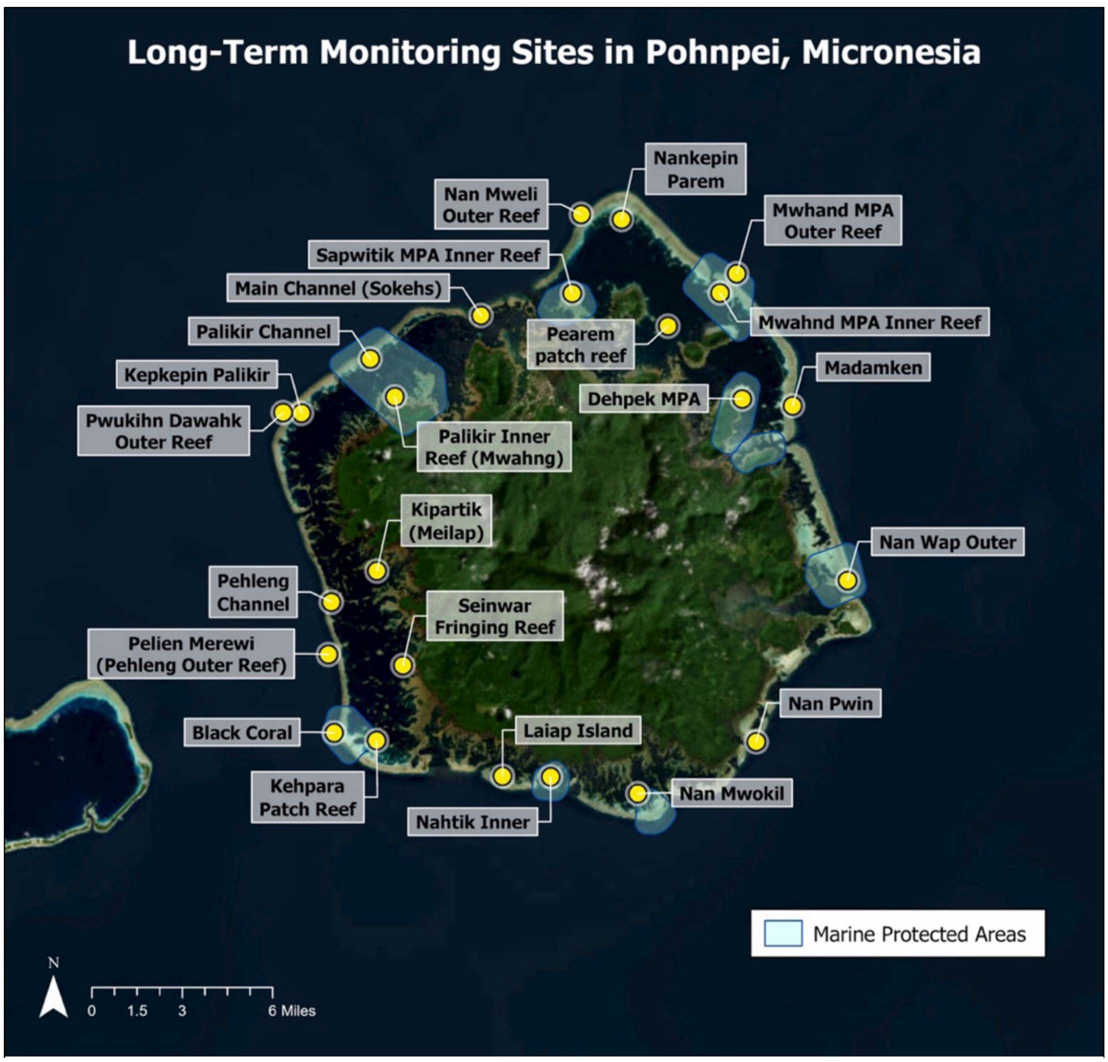



*Figure 2. Location of the 24 long-term monitoring sites used in this analysis. These sites have been formally monitored since 2012 with support from MCRM.*

At each site, five 50-meter transects were used to assess coral and other benthic assemblages. Surveys were conducted at depths of 8–10 meters on outer reefs and 3–5 meters within inner lagoon reefs. A single depth range was chosen for each reef type to maximize the number of monitoring sites while remaining within logistical constraints.

The photographs used in this study were taken in late November 2024, and according to NOAA's Coral Reef Watch, sea surface temperatures at that time had exceeded 12 Degree Heating Weeks (DHW). Photo-quadrat imagery analysis was used to assess benthic substrate composition. Along each 50-meter transect, 50

photographs were taken at 1-meter intervals, totaling 250 images per site. These images were analyzed using CoralNet, an online repository and tool for benthic image analysis maintained by the University of California, San Diego. Within each image, substrate composition is identified using five randomly placed reference points.

To characterize bleaching, bleached corals selected from the randomly placed reference points were categorized into three severity categories: recently dead, fully bleached, or paling. This classification was recorded separately in a spreadsheet alongside the CoralNet annotations. It's important to note that while identifying benthic substrate on CoralNet, bleached corals were not marked as bleached within the program, only on the separate excel sheet. To maintain consistency in data interpretation, bleaching characterization was carried out by a single researcher.

<u>Bleaching Severity and Trend Analysis</u>

Bleaching data were analyzed in R to examine spatial and taxonomic patterns of coral bleaching severity around Pohnpei. For each monitoring site, the number of photo-quadrat points classified as *fully bleached*, *paling*, *unbleached*, or *recently dead* was tallied. To assess site-level bleaching severity, proportions were calculated for each category. In this analysis, *fully bleached* and *recently dead* corals were combined as a proxy for coral loss, under the assumption that both categories likely indicate mortality. An additional "overall bleaching" metric, encompassing *paling*, *fully bleached*, and *recently dead*, was used to capture the full extent of coral stress at each site.

To explore spatial variation in bleaching susceptibility, sites were grouped by reef type (inner vs. outer) and geographic region (north-east, south-east, north-west, and south-west). These groupings enabled comparisons of bleaching severity across different environmental contexts.

In addition to site-level trends, species- and taxon-level patterns were evaluated using annotations generated in CoralNet. For each site, the relative abundance and bleaching prevalence of individual coral taxa or species were calculated. This allowed for a comparison of common groups such as *Porites* and *Acropora* to identify which were more susceptible or resistant to thermal stress. The analysis shifted between taxon- and species-level detail depending on its intended application, for instance, species-level results may better inform coral restoration efforts, while broader taxonomic patterns provide insight into ecological trends.

Note on Abundance vs. Severity-Only Charts: Charts that include both abundance and bleaching severity offer insight into how dominant a species is and how affected it was, with severity shown in proportion to total observations at the site. In contrast, charts that show severity only treat each species or site equally, regardless of how frequently they were observed, which is useful for comparing susceptibility across taxa but may underrepresent dominant groups.

<u>Integration of Environmental Context and Historical Trends</u>

While the primary focus of this analysis is on the 2024 bleaching event, past disturbances bleaching events were also considered to provide ecological context. Although high-resolution photo-quadrat imagery was not available for those earlier events, data from long-term monitoring were used to infer historical trends in coral cover, mortality, and recovery. These earlier data helped identify sites that previously demonstrated resilience or decline, allowing for a more nuanced interpretation of current patterns and potential recovery trajectories.

<u>Spatial Visualization</u>

**Bleaching Severity Visualization:** While quantitative data analysis was conducted in R, ArcGIS Pro was used to create summary maps for visual interpretation of spatial patterns. Figure 5 and 6 display the prevalence of coral bleaching at each of the 24 long-term monitoring sites surveyed in November 2024. The size of the symbols at each site reflects the proportion of corals observed as paling, fully bleached, or recently dead, with a graduated color scale used to represent bleaching severity. Bleaching data were binned using standard deviation intervals, with each class representing a one standard deviation range from the mean. The "overall bleaching" metric was used for this visualization.

**Species Composition Visualization:** To visualize coral community composition, long-term monitoring data collected sites across Pohnpei between 2012 and 2025 were used. For each site and selected timepoint, the top five coral groups were identified by ranking groups based on total live coral cover. To reduce complexity and highlight ecologically relevant patterns, species were grouped into simplified categories based on ecological and management interest. For example, *Acropora*, *Montipora*, and *Porites rus* were retained as distinct categories, while less abundant or functionally similar species were grouped into broader categories such as "Merulinidae" or "Other Coral." Grouping rules were consistent across all timepoints and visualizations. To allow for comparison across sites and years, coral cover values for the top five taxa were normalized using the formula:

$$\text{(relative percent cover)} = \text{(species cover} \div \text{total coral cover at site and timepoint)} \times 100$$

The resulting proportions were visualized as pie charts using R. For the 2024 bleaching survey, each site is represented by a single pie chart showing species composition at the time of the thermal stress event (see Figure 5 and 6). A second visualization (Figure 7) shows temporal changes in species composition at selected long-term monitoring sites across four timepoints:

- **2012/2014**: Earliest available baseline per site
- **2018/2019**: Post-bleaching period following the 2016–2017 thermal stress events
- **2024**: Recovery trajectory and composition prior to the most recent bleaching event
- **2025**: Response following the 2024 bleaching event

Each box in the time series graphic corresponds to one site, with one pie chart per timepoint. Final visual layouts were created in ArcGIS Pro to illustrate both spatial patterns and temporal trends in coral assemblages alongside bleaching severity. This time series dataset enabled site-level comparisons of taxonomic shifts and the identification of ecological trends over more than a decade. The data were used to assess changes in community composition, identify potential phase shifts, and infer coral recovery potential or resilience based on the persistence, loss, or emergence of key taxa like *Acropora*, *Montipora*, and *Porites*. These insights informed interpretation of the 2024 bleaching event and supported management recommendations for identifying resilient reef areas and climate refugia.

Limitations and Assumptions

This analysis is based on a snapshot of coral condition during an active thermal stress event in November 2024 and does not yet capture long-term outcomes such as recovery or mortality. As such, several assumptions were made to interpret observed bleaching patterns within a management-relevant timeframe. Specifically, colonies that were fully bleached were treated as likely to result in mortality, while paling colonies were assumed to have a higher likelihood of recovery. While this approach introduces uncertainty, since outcomes can vary based on species, stress duration, and site-level conditions, it reflects the urgent need for timely decision-making in the face of ongoing climate threats. For example, this method may overestimate mortality in species like *Porites massive***,** which have been observed to recover even after fully bleaching under certain conditions. Follow-up recovery surveys are needed to validate these assumptions and refine our understanding of species- and site-level responses.

This analysis also assumes that patterns observed in long-term monitoring data from 2012 to 2024 can be used to infer apparent recovery or resistance from past bleaching events. While this provides useful historical context, it remains an assumption, as consistent post-bleaching monitoring was not always available during those years to fully track resistance and recovery trajectories.

While limitations are inevitable in near-real-time assessments, the value of this analysis lies in its ability to provide actionable insights to support urgent conservation decisions. As more data become available, these insights can and should be refined.

## Results and Key Findings

Island-Wide Coral Community Composition:

Across all long-term monitoring sites, coral community composition was heavily dominated by *Porites* species (Figure 3). The most observed species was *Porites massive* (PORMAS), accounting for 27.6% of all coral points, followed by *Porites rus* (PORRUS, 26%) and *Porites cylindrica* (PORCYL, 11.8%). Together, these three species made up nearly two-thirds of all coral observations.

Long-term monitoring data show that *Acropora* declined in island mean cover from 3.22% ± 2.38% CI (SD = 5.75%) in 2012 to 1.89% ± 1.89% CI (SD = 4.46%) in 2024, representing one of the most significant island-wide changes. In contrast, *Porites massive* increased from 6.3% ± 2.6% CI (SD = 6.3%) in 2012 to 11.2% ± 3.4% CI (SD = 8.1%) in 2024. Other genera also showed increases during this period, including *Platygyra* (0.28% ± 0.32% CI to 1.17% ± 0.89% CI) and *Montipora* (0.68% ± 0.38% CI to 1.83% ± 1.64% CI). These trends suggest a broader shift in coral community composition, marked by species reshuffling likely driven by repeated bleaching and other environmental stressors.

Species-Level Bleaching Resistance (Figure 3 and 4):

In 2024, *Porites rus* (1.9% fully bleached) and *Porites cylindrica* (8.5% fully bleached) exhibited strong resistance across nearly all sites, despite being one of the most abundant species (37.7% of all observations).

Fully bleached *Porites rus* colonies were observed only at inner reef sites. *Porites massive* (35.4% fully bleached) and *Montipora* species (19.8% fully bleached) showed moderate vulnerability, while *Acropora* species exhibited extreme susceptibility, with 88.6% fully bleached.

Spatial Patterns in Bleaching:

Outer reef sites experienced higher average bleaching (52.8% ± 8.9% CI) than inner reef sites (29.2% ± 5.2% CI). Although, this difference may be partially explained by differences in coral community composition: outer reefs had a higher proportional cover of bleaching-sensitive genera such as *Acropora* (Figure 6), while inner reefs were dominated by more heat-tolerant taxa like *Porites* (Figure 5). The two outer reef sites that showed lowest bleaching severity (Figure 6), Nan Wap Outer Reef and Main Channel (Sokehs), are located right outside of channels. Bleaching rates inside MPAs (37.7% ± 7.4% CI) were similar to those outside MPAs (38.2% ± 9.6% CI).

Site-Specific Patterns:

The following analysis groups sites based on observed bleaching responses and shifts in coral community composition between 2012 and 2025. Corals were grouped into major taxonomic categories: *Acropora*/*Montipora*, *Merulinidae*, *Porites rus*, *Porites cylindrica*, *Porites massive*, and “other coral.” Sites that exhibited low bleaching across most taxa (<30% effected) include Kipartik (Meilap), Pearem Patch Reef, Kepkepin Palikir, Palikir Inner Reef (Mwahng), Nan Mwokil, Kehpara Patch Reef, Dehpehk MPA, Seinwar Fringing Reef, Main Channel (Sokehs), and Laiap Island (Figure 5 and 6). All of these are inner reef sites, except Main Channel (Sokehs).

Bleaching observations at Nan Mwokil showed 12.8% full bleaching and 9.1% paling across taxa (Figure 8). Species-level data reveal that effected *Acropora*, *Montipora*, and *Porites massive* colonies exhibited signs of paling but rarely full bleaching (Figure 9). The coral community was dominated by “Other Coral” (11.6%), *Montipora* (9.52%), and *Porites massive* (7.36%). Historical data indicate a decline in *Acropora* abundance (from 17.36% in 2014 to 0.4% in 2024), along with a shift to a more heat tolerant coral assemblage (Figure 7).

Shifts in coral community composition were observed at multiple locations. At Nan Wap Outer, both *Acropora* and *Montipora* experienced sharp declines and were replaced by *Porites rus* and *Porites cylindrica* (Figure 7), indicating a change in dominant coral taxa. Montipora abundance has increased particularly in areas where *Acropora* had historically been more prominent, including Madameken, Mwhand MPA Outer Reef, Nan Mwokil, and Nan Pwin (Figure 7).

Several sites that were previously dominated by *Acropora* showed signs of resistance and/or recovery following the 2016–2017 bleaching events (Figure 7). In many of these locations, such as Madamken, Nan Pwin, and Mwahnd MPA Outer Reef, *Acropora* rebounded significantly in just 3-5 years following those events. For example, *Acropora* cover at Madamken dropped from 18.7% in 2012 to just 3.0% in 2018, but rebounded to 21.0% by 2024, surpassing pre-bleaching levels before the most recent crash. However, these same sites experienced severe bleaching again in 2024, with *Acropora* cover dropping to zero in the most recent surveys.

In contrast, sites such as Nan Mwokil, Sapwitik MPA, Kipartik (Meilap), Kepkepin Palikir, and Palikir Inner Reef retained remnant *Acropora* populations through the 2024 event, suggesting localized conditions or ecological factors that may support persistence despite repeated stress.

## Interpretation

This analysis provides insight into species-level and site-level coral bleaching resistance across Pohnpei during the 2024 thermal stress event, with implications for understanding ecological resilience and guiding management efforts.

Feeding Strategy Matters:

As anticipated, species with massive or encrusting morphologies, like *Porites rus*, *Porites cylindrica*, and *Porites massive*, consistently exhibited low full-bleaching rates, despite being dominant across the reef system (Figure 4). This aligns with the well-established pattern that thicker-tissue, slow-growing corals tend to be more thermally tolerant (Marshall and Baird 2000; Van Woesik et al. 2016).

Corals like *Porites rus* are also more heterotrophic, meaning they can supplement their energy needs by feeding on plankton or organic material in the water column, a trait associated with greater bleaching resistance, especially in nearshore, nutrient-enriched environments (Wooldridge et al. 2014). In contrast, highly autotrophic genera such as *Acropora*, rely more heavily on photosynthesis via their symbiotic algae and may be more vulnerable to thermal stress. While this analysis did not assess trophic strategy directly, it likely contributes to the observed resilience of certain taxa.

Interestingly, the response of *Montipora* species did not align neatly with prior expectations. Although traditionally considered thermally sensitive (Brown et al. 2023; Pratchett et al. 2013), *Montipora* showed only moderate levels of full bleaching during the 2024 event, suggesting that additional traits, such as environmental context or site-level variability, may be influencing their response.

Dominance of Porites and Community Restructuring:

*Porites* species continue to dominate the coral community across Pohnpei, both in terms of abundance and bleaching resistance (Figure 3). Their prevalence may reflect both biological resilience and a gradual shift in reef composition toward more heat-tolerant species. Similarly, the increasing presence of *Platygyra* and *Montipora* at some sites suggests subtle but significant restructuring in response to repeated disturbances. These trends may indicate the emergence of an alternative stable state.

In contrast, *Acropora* species, once key structural contributors to reef complexity, have declined across most sites. This is especially concerning given their ecological role and their extreme vulnerability to bleaching, with nearly 89% of colonies fully bleached in 2024. The near-total loss of *Acropora* at historically dominated sites such as Madamken, Nan Pwin, Mwhand MPA, and Nan Wap Outer Reef emphasizes the cumulative impact of back-to-back bleaching events.

Some of these sites had previously shown promising signs of recovery after the 2016–2017 events, surpassing pre-bleaching levels before the most recent crash. These rebounds highlight *Acropora*'s capacity for rapid regrowth under favorable conditions. So, the fact that *Acropora* failed to persist through the most recent thermal stress event raises questions about whether these populations will recover again, or if we are witnessing the early stages of a more permanent shift in community structure at these sites. Notably, all of the sites exhibiting this pattern are outer reefs located on the island's east side.

It's important to recognize that this analysis captures coral condition immediately after the 2024 thermal stress event, as the 2025 time point reflects assumed mortality. *Acropora* is known to bleach easily and die quickly under thermal stress, but it is also one of the fastest-growing coral genera and has the capacity to recover rapidly under the right conditions. Whether these populations will bounce back again remains to be seen. What we can say now is that repeated stress events have not increased *Acropora*'s resistance to bleaching at these sites.

The observed rise in *Montipora* is also worth noting. Increases in abundance is seen at sites that were once dominated by *Acropora* in 2012/2014. While primarily encrusting on outer reefs, *Montipora* at inner reef sites often exhibits branching and plating growth forms, potentially filling the structural and ecological roles that *Acropora* once held. These shifts may have significant implications for reef structure and ecosystem function, particularly if the new assemblages differ in growth form, habitat provisioning, or reproductive dynamics.

<u>Remnant Acropora and Signs of Persistence:</u>

Despite these losses, a few sites have retained small but persistent *Acropora* populations. These include Sapwitik MPA, Kipartik (Meilap), Nan Mwokil, Kepkepin Palikir, and Palikir Inner Reef. These 4 sites are all inner reef sites on the West side of the island and exhibit generally high resistance to bleaching. While *Acropora* abundance at these sites is low, their continued presence suggests favorable environmental conditions or increased tolerance within the coral populations themselves. Their persistence warrants continued monitoring and scientific investigation to better understand both the drivers of their resistance and the factors limiting their full recovery, whether ecological, environmental, or genetic.

<u>Spatial and Site-Specific Patterns:</u>

Bleaching resistance varied spatially across Pohnpei's reef systems. Inner reef environments generally experienced lower bleaching severity than outer reef sites (Figure 5 and 6), a pattern consistent with the literature (Van Woesik et al. 2025). Yet exceptions, like Main Channel (Sokehs) and Nan Wap Outer Reef, highlight the importance of fine-scale environmental factors such as proximity to channels or upwelling (Figure 6). This suggests that reef type alone does not fully predict bleaching outcomes and highlights the importance of site-specific characteristics.

Bleaching levels inside and outside of Marine Protected Areas (MPA) were nearly identical in this event (37.7% vs. 38.2% bleached), suggesting that protection status alone may not determine bleaching resistance. This aligns with other studies showing that while MPAs improve ecological health by increasing fish biomass (Houk el. Al 2022), they do not inherently buffer reefs from thermal stress unless paired with resilience-based site selection.

Nan Mwokil demonstrated consistently low bleaching across all taxa, including *Porites massive*, *Montipora*, and even remnant *Acropora* populations (Figure 8). The persistence of vulnerable genera in this location suggests the presence of environmental or biological factors that buffer against bleaching. When looking at long-term trends, *Acropora* at Nan Mwokil declined following the 2016–2017 events, but community composition and abundance has remained relatively stable ever since (Figure 7). It's also not only stable, but diverse. Unlike many sites where stability is characterized by dominance of heat tolerant *Porites* species, Nan Mwokil has retained high taxonomic diversity (Figure 7). Nan Mwokil's resistance, coupled with long-term shifts in community structure, indicates it may be functioning as a natural refugia. Main Channel (Sokehs) and Laiap Island show a similar pattern of stable diversity, highlighting the potential for some reefs to persist in altered, but still resilient, ecological states.

Nan Wap Outer offers a strong example of phase shift following repeated disturbances. The site has experienced a dramatic decline in both *Acropora* and *Montipora*, with Porites species now dominating (Figure 7). These transitions reflect long-term phase shifts in reef community structure, likely driven by cumulative disturbances, and raise important questions about how ecosystem function and resilience will change as different assemblages become more common.

<u>Implications for Monitoring and Management:</u>

Together, these findings suggest that coral resistance and community composition in Pohnpei are dynamic, site-specific, and shaped by both species' traits and environmental factors. To guide resilience-based management, sites can be grouped into three functional categories:

1. Resistance

These reefs exhibited low bleaching severity in 2024. Some maintained or even increased the presence of vulnerable species like *Acropora*. Notable examples include Nan Mwokil, Kipartik (Meilap), Palikir Inner Reef, and Kepkepin Palikir. These reefs may function as natural climate refugia and should be prioritized for protection based on local interests. They are strong candidates for adaptive management experiments, such as installing temperature loggers and conducting fine-scale environmental monitoring to help link local thermal patterns to coral responses. Doing so can help identify the environmental factors that support resistance and allow managers to apply those insights more broadly. Sites like Nan Mwokil, Main Channel (Soekhs), and Laiap Island are particularly important. Not only do they show resistance, but they also retain high coral diversity. This suggests the emergence of alternative stable states that may be critical for long-term reef persistence.

Consistently lower bleaching on inner reefs suggests they may offer some natural buffering capacity. However, this natural advantage is only useful if land-based threats are controlled. This highlights the importance of watershed management to reduce sedimentation, nutrient loading, and runoff, especially near reefs that show promise for resilience.

2. Recovery (*Acropora*-focused)

These reefs, including Madamken, Nan Pwin, and Mwahnd MPA Outer Reef, demonstrated recovery after past bleaching events but were hit hard again in 2024. Their past resilience suggests recovery is possible, but continued monitoring is needed to determine whether they rebound or shift more permanently. Understanding what enabled previous recovery, whether ecological traits or environmental conditions, can help refine restoration timelines and guide where and how to intervene. These sites offer an opportunity to learn from past success and potentially replicate those conditions elsewhere. Additional analysis could help clarify recovery trends in other coral species of management interest, providing further insight into where and how restoration efforts might be most effective.

3. Shifting or Declining

Some sites appear to be transitioning away from *Acropora* dominance toward more stress-tolerant communities (e.g., *Montipora*, *Porites*) or are showing signs of broader coral decline. These includes Nan Wap Outer, Mwahnd MPA Outer Reef, and Nan Pwin. A key question is whether these new communities provide the same structural and ecological functions as previous *Acropora*-dominated reefs. For example, does *Montipora* offer the same habitat complexity that *Acropora* once did? If so, restoration could support their persistence and resilience under future climate stress. If not, more active or alternative interventions may be needed to avoid further degradation.

While Marine Protected Areas (MPAs) have long been a cornerstone of reef protection, this analysis reinforces growing evidence that MPA status alone does not buffer reefs from thermal stress. Future MPA design should integrate site-specific resilience indicators, such as local thermal histories, bleaching resistance, and current coral community composition.

Other Restoration Considerations:

Looking ahead, restoration efforts should diversify beyond fast-growing *Acropora*. Species like *Montipora, Platygyra*, and *Porites massive*, which demonstrated moderate resistance and increasing cover, may be viable candidates for species diversification in reef restoration planning. Additionally, reefs with remnant *Acropora* populations, however sparse, should be prioritized for further investigation. Identifying the conditions that support their persistence, and the factors limiting their full recovery, could inform both restoration strategies and climate adaptation planning. Genetic testing of surviving colonies could also help identify stress-tolerant genotypes that may be critical for future propagation efforts. Site selection for restoration should be guided by recent bleaching outcomes, community trajectories, and environmental context. Prioritizing resistant or recovering reefs with high functional value will maximize the chances of restoration success under future climate scenarios.

## Recommendations for Reef Managers

Based on the 2024 bleaching event analysis and long-term monitoring data, the following actions are recommended to support coral reef resilience and adaptive management in Pohnpei:

Monitoring and Protection

- Conduct repeat surveys sometime in the next year to assess recovery. Due to the assumptions used in this analysis (see *Limitations and Data Needs* section), recovery surveys are essential for validating patterns and refining insights.
- Install temperature loggers at key sites (e.g., Nan Mwokil, Laiap Island, or Main Channel) to gather fine-scale data on thermal conditions.
- Conduct fine-scale environmental monitoring at key sites. Collect data on factors such as currents, chlorophyll levels, and water quality to better understand the local environmental drivers of coral resistance.
- Review current MPA boundaries and management plans to assess whether they include reefs showing high resistance or the presence of vulnerable species. Where gaps exist, advocate for resilience-based expansion (e.g., species resistance, thermal refugia) or stronger protections.

Restoration and Species Management

- Expand restoration focus beyond *Acropora* to include more thermally tolerant genera that are already increasing in abundance like *Montipora*, *Platygyra*, and *Porites massive*.
- Conduct genetic testing on surviving *Acropora* colonies to identify and propagate heat-tolerant genotypes.
- Evaluate whether new coral assemblages (e.g., Montipora) maintain structural and ecological roles, and support their persistence where appropriate.

Land-Based Threat Reduction

- Reduce land-based pollution, especially from infrastructure-heavy areas on Pohnpei's north coast, to support inshore reef resilience.
- Improve watershed management and promote best practices for erosion control and wastewater treatment.

Community Engagement and Communication

- Integrate climate refugia and bleaching resistance into local outreach and planning tools, such as community presentations, permitting processes, or reef use zoning.

Continue to Invest in Long-Term Monitoring and Local Capacity

- This study was only possible because of the long-term datasets established by the Micronesia Coral Reef Monitoring Program and local monitoring efforts. Continued support for consistent monitoring and local capacity to analyze and act on that data is critical for responding to future events in real-time.

## Areas for Future Research

This project provides a foundation for identifying patterns of coral resistance and community change, but additional research is needed to better understand the mechanisms driving resilience in Pohnpei and across the region. Although this analysis did not include a formal resilience model, preliminary comparisons of coral community composition from 2012 to 2024 suggest potential signs of ecological memory, specifically, the persistence of certain taxa through multiple bleaching events. These shifts offer a valuable starting point for future studies to examine how past exposure shapes coral responses to repeated heat stress. In addition to species persistence, other indicators of ecological memory could include shifts in dominant life-history strategies (e.g., toward stress-tolerant species), increased resistance or faster recovery in previously impacted areas, or evidence of physiological acclimatization at the colony or population level. Species-specific time series analyses, along with environmental and trait-based data, could help determine whether recovery trajectories align with ecological memory theory and inform more targeted strategies for conservation and restoration.

Recommendations for Future Research:

- **Modeling resistance drivers:** Future studies could apply formal modeling approaches to identify the ecological and environmental variables most strongly associated with coral resistance. Incorporating long-term data on coral cover trajectories, bleaching severity, and taxonomic shifts may reveal how specific site characteristics influence resilience outcomes.
- **Environmental data integration:** Expanding datasets to include site-level environmental variables, such as temperature, chlorophyll-a concentrations, turbidity, and nutrient levels, could improve understanding of local stressors and conditions that buffer against bleaching.
- **Community composition and memory indicators:** Further analysis of life-history strategies, species persistence, and recovery dynamics could help detect signatures of ecological memory. Exploring how coral communities reorganize after repeated bleaching events may shed light on longer-term adaptation or regime shifts.
- **Comparative analysis across Micronesia:** Applying similar analytical frameworks across other islands and states in the Federated States of Micronesia would clarify whether observed patterns in Pohnpei reflect localized ecological memory or broader regional dynamics. This could support regional-scale planning for reef adaptation and conservation.

# Figures and Charts

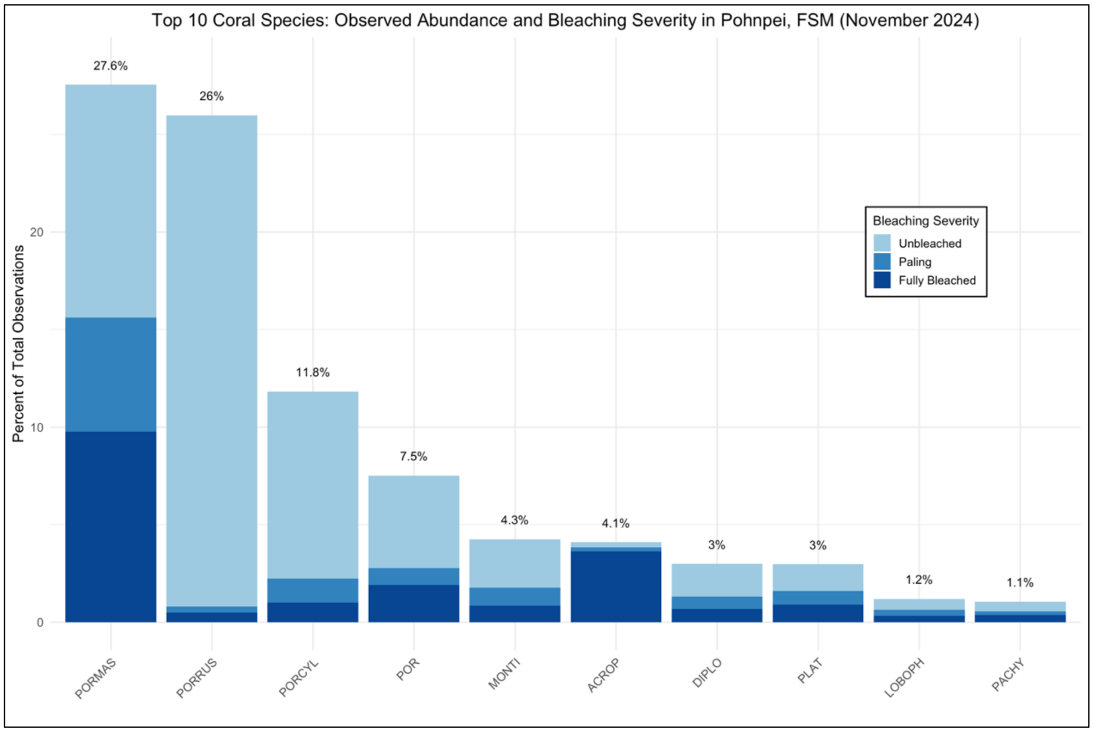



*Figure 3. Relative abundance and bleaching severity of the top 10 most common coral species observed at long-term monitoring sites in Pohnpei, Micronesia, during the November 2024 bleaching event. Bar height represents each species' percent contribution to the total coral observations. Bars are segmented by bleaching severity: dark blue for fully bleached, medium blue for paling, and light blue for unbleached.*

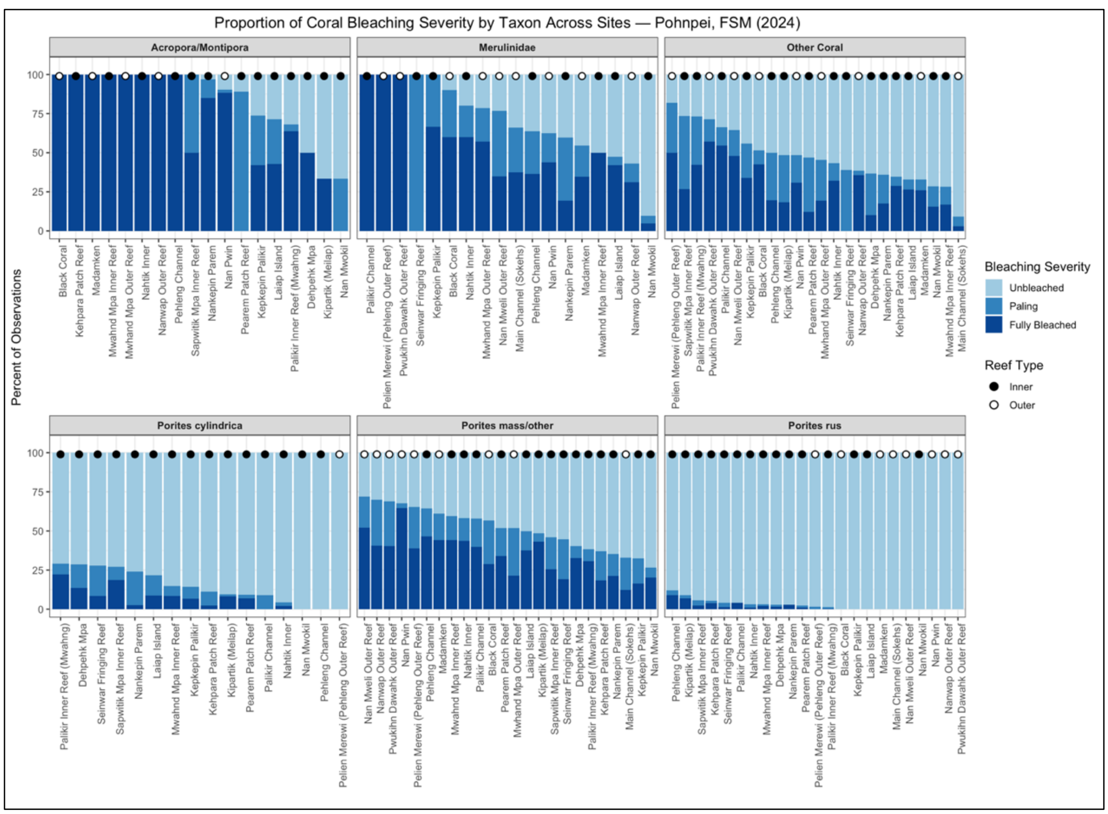
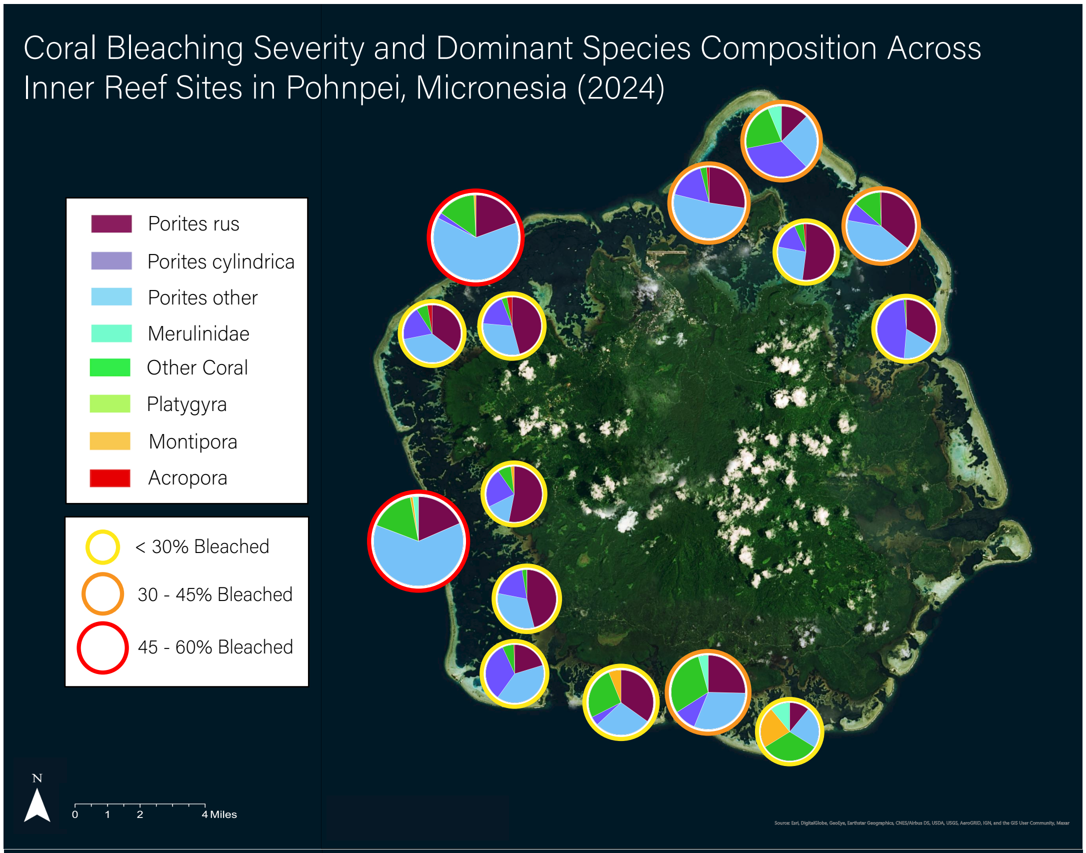



*Figure 4. Percent of coral colonies bleached by taxon across long-term monitoring sites in Pohnpei, FSM (2024). Panels display bleaching severity for six major coral groups, with sites ordered by percent bleached within each taxon. Points are color-coded by reef type: black indicates inner reef sites, and white indicates outer reef sites. This graph treats each taxon equally, regardless of how frequently they were observed.*



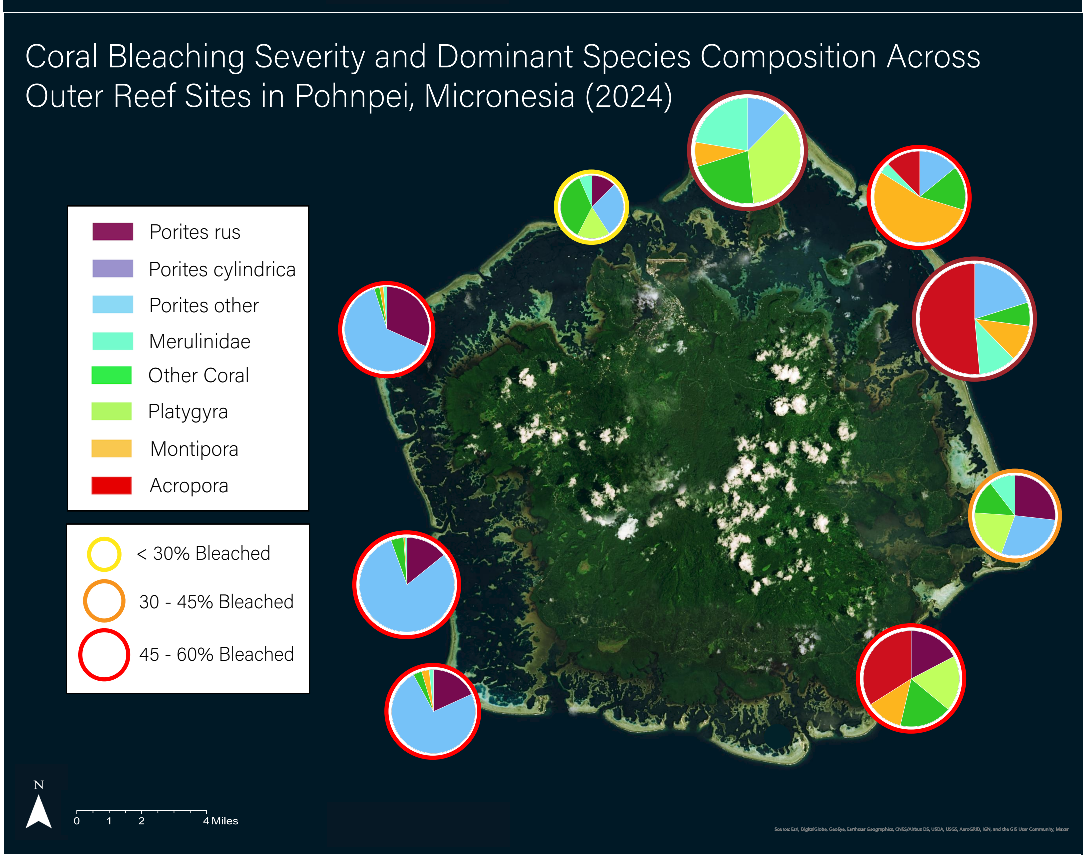




*Figure 5 and Figure 6. Coral bleaching prevalence at inner (above) ad outer (below) reef sites in Pohnpei, Micronesia (November 2024). Outer ring color denotes the overall proportion of colonies exhibiting bleaching (paling, full bleaching, or recent mortality), with chart size scaled to relative bleaching severity. Internal pie charts illustrate the five most abundant coral taxa recorded at each site during the November 2024 bleaching survey.*

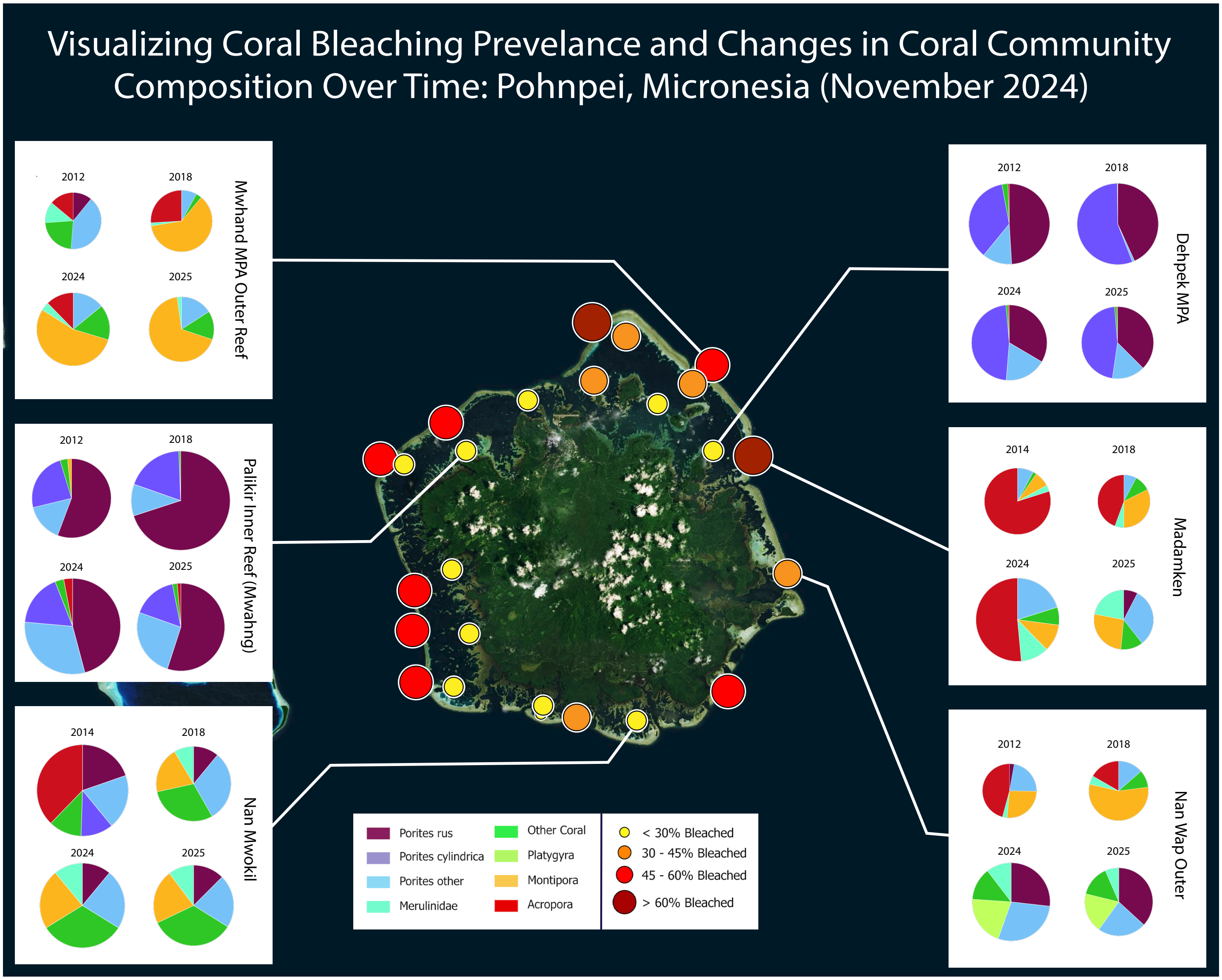



*Figure 7. Coral community composition and bleaching severity at long-term monitoring sites in Pohnpei. Pie chart size reflects total live coral cover at each site during the survey period, while pie segments represent the five most abundant coral species. The color and size of the symbols on the map indicate the percentage of coral colonies showing signs of paling, full bleaching, and recent mortality during the 2024 bleaching event.*

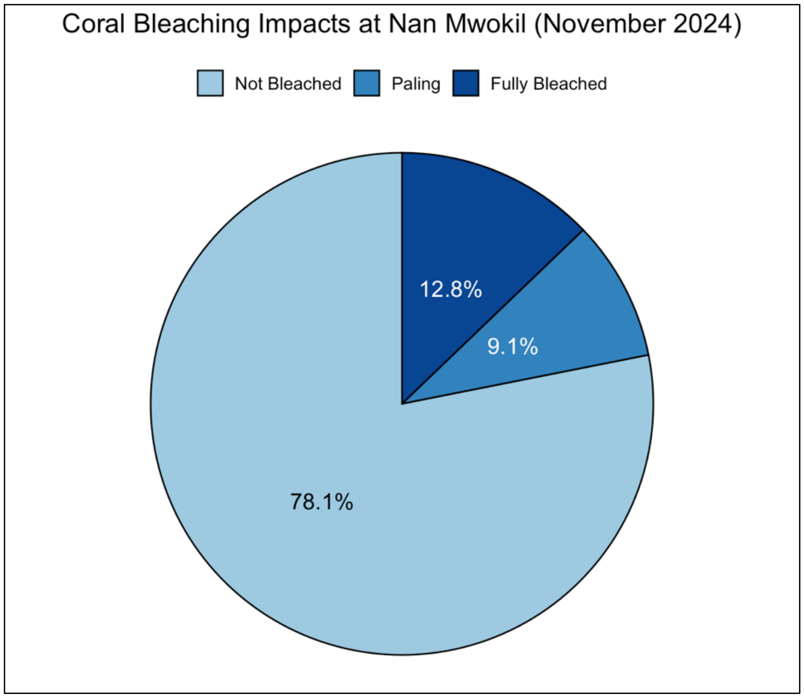



*Figure 8. Illustrates coral observations categorized by bleaching severity at Nan Mwokil. Dark blue for fully bleached, medium blue for paling, and light blue for unbleached.*

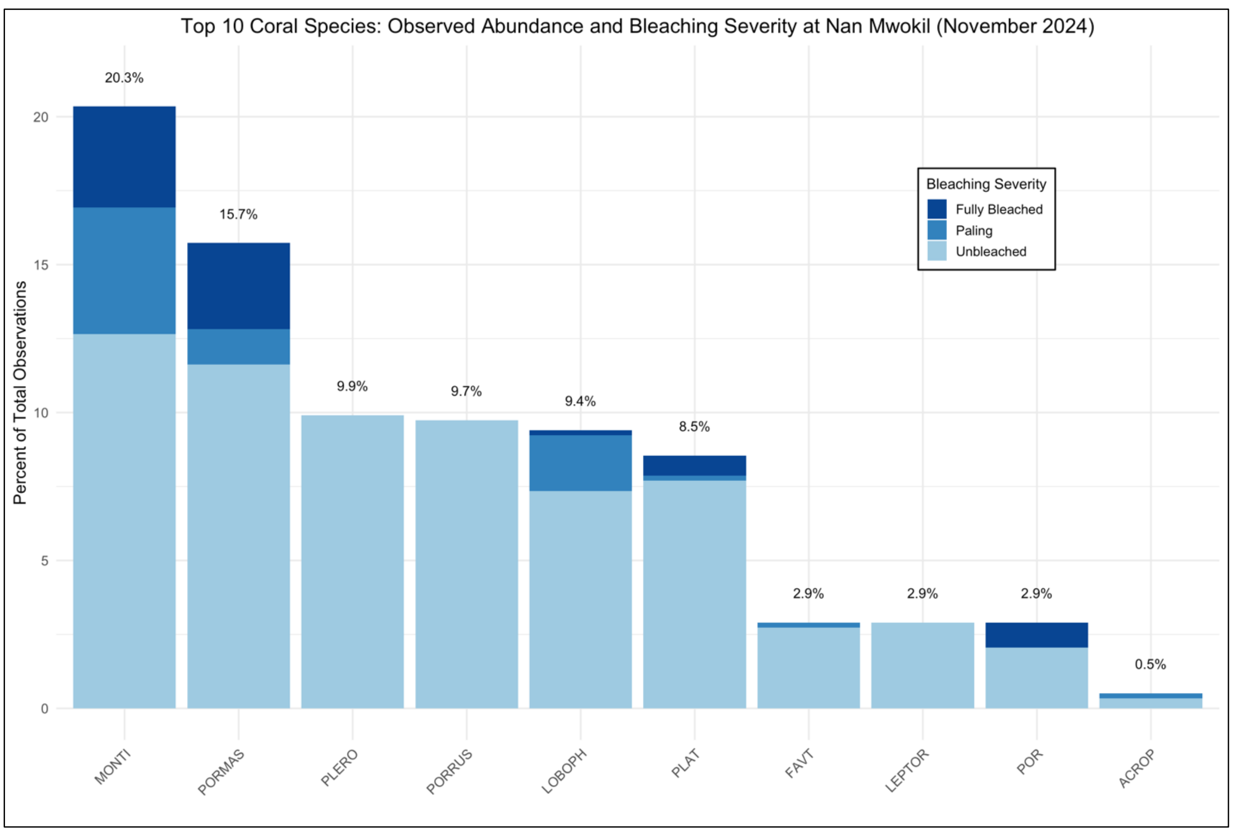



*Figure 9. Relative abundance and bleaching severity of the top 10 most common coral species observed at Nan Mwokil, a long-term monitoring site on the SE side of Pohnpei, Micronesia. Bar height represents each species' percent contribution to the total coral observations at this site. Bars are segmented by bleaching severity: dark blue for fully bleached, medium blue for paling, and light blue for unbleached.*

## Conclusion

Pohnpei's coral reefs are experiencing an unprecedented escalation in bleaching events. In just the past decade, the island has gone from recording no mass bleaching to enduring three major events. This is not part of a natural cycle. It is a clear signal of accelerating climate impacts. Yet, even in the face of escalating stress, this analysis offers a measure of hope.

By synthesizing data from 24 long-term monitoring sites and over a decade of historical records, this study highlights patterns of resilience that can inform future management. Some reef sites continue to resist bleaching, certain vulnerable coral species persist, and spatial patterns in resistance are emerging. These findings point to opportunities for action: protecting likely refugia, prioritizing adaptive species for restoration, and investing in fine-scale monitoring to uncover the drivers of resilience. They also underscore the critical role of watershed management in safeguarding nearshore reefs already showing signs of natural resistance.

This work contributes to climate adaptation and conservation in Pohnpei by translating scientific observations into actionable insights. In a rapidly changing climate, the ability to respond locally, with strategies grounded in site-specific data, will be essential. This report lays a foundation for continued adaptation and targeted conservation efforts that can protect both coral reef ecosystems and the livelihoods they support.

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Finally, thank you to the communities of Pohnpei for their ongoing stewardship of the island's coral reefs. This work is dedicated to supporting local efforts to protect and sustain these ecosystems in the face of climate change.

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