Coral Reef Evaluation and Monitoring Project (CREMP)

Assessing the Health and Trends of Florida’s Coral Reef Ecosystem

Prepared by
Dhruvil Mandaviya
April 2025

Linkedin	https://www.linkedin.com/in/dmandaviya
Github	https://github.com/DMANDAVIYA
Email	dmandaviya0369@gmail.com

Jupyter Notebook file available at:
https://github.com/DMANDAVIYA/Coral-Reef-Evaluation-and-Monitoring

Credits:
Florida Fish and Wildlife Conservation Commission - Fish and Wildlife Research Institute and the CREMP Team and Collaborators. The Coral Reef Evaluation and Monitoring Project (CREMP) in the Florida Keys is managed by the Corals Research Program and the Fish and Wildlife Research Institute and funded by the Environmental Protection Agency as part of the Florida Keys National Marine Sanctuary Water Quality Protection Program.

Table of Contents

1. Introduction

Florida's coral reef ecosystem, the third-largest barrier reef system worldwide, represents a vital natural treasure, providing a multitude of ecological and economic benefits.[1] These underwater habitats support an extraordinary diversity of marine life, sheltering over 4,000 species of fish, corals, and other organisms within less than one percent of the ocean floor, yet serving as home to a quarter of all marine species.[2] Beyond their ecological significance, coral reefs are crucial to Florida's economy, aflracting tourists from around the globe for recreational activities such as diving, snorkeling, and fishing.[2] The revenue generated by these activities, along with the associated hospitality and service industries, contributes billions of dollars to the state's economy. Furthermore, these intricate reef structures act as natural coastal defenses, dissipating wave energy from storms and floods, thereby protecting shorelines from erosion and potentially saving lives and preventing property damage.[2]

Despite their immense value, Florida's coral reefs face increasing threats that have led to significant declines in their health and extent.[1] These threats are multifaceted, encompassing both global and local stressors. Climate change, manifested through rising ocean temperatures, causes coral bleaching, a phenomenon where corals expel the symbiotic algae living in their tissues, leading to starvation and death if prolonged.[4] Ocean acidification, another consequence of increased atmospheric carbon dioxide, hinders the ability of corals to build and maintain their calcium carbonate skeletons.[4] Local stressors further exacerbate these issues, including pollution from land-based runoff carrying sediments, nutrients, and toxic substances, as well as physical damage from marine debris, overfishing, and vessel groundings.[3] In recent years, Florida's Coral Reef has been severely impacted by Stony Coral Tissue Loss Disease (SCTLD), a highly lethal disease that has caused widespread mortality among many reef-building coral species.[6] The combined effects of these pressures underscore the urgent need for comprehensive and sustained monitoring efforts to understand the status and trends of these vital ecosystems.

1.1. Overview

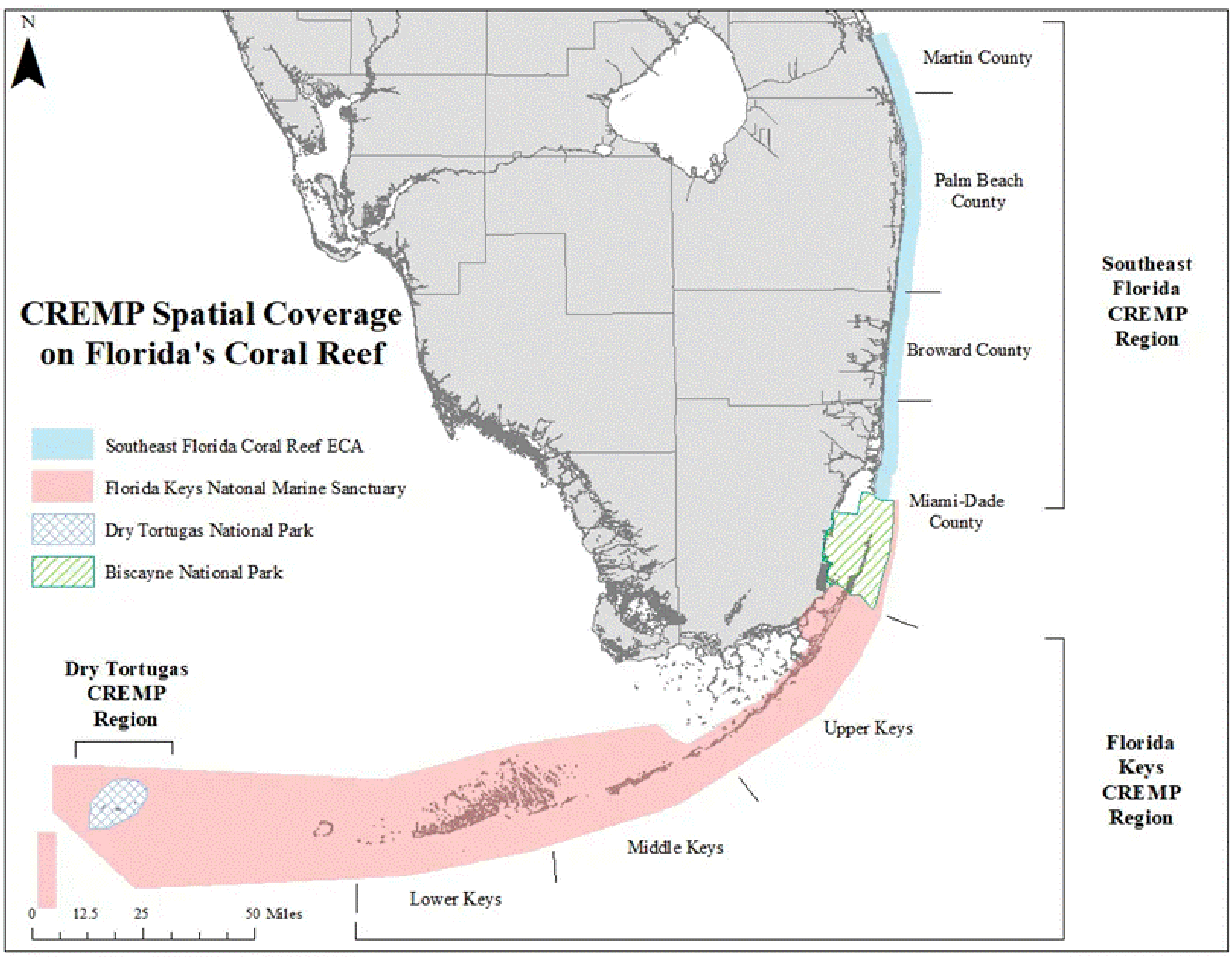
The Coral Reef Evaluation and Monitoring Project (CREMP) stands as a vital long-term and spatially extensive program dedicated to monitoring the health of coral reefs along Florida's Coral Reef, spanning from Martin County to the Dry Tortugas. Initiated in 1996, CREMP plays a crucial role in documenting both short-term and long-term changes in benthic communities across this significant reef ecosystem. This report provides a comprehensive overview of CREMP, detailing its history, objectives, and the evolution of its monitoring methodologies. It further examines the key metrics employed in coral reef monitoring, the factors influencing reef health as observed through CREMP, the early warning indicators of coral decline identified by the project, and the potential for CREMP data to contribute to predictive models of coral reef evolution. Finally, the report places CREMP within a global context by comparing it with other significant coral reef monitoring programs, underscoring its importance for coral reef conservation and management efforts in the face of increasing environmental challenges. Introduction: The Coral Reef Evaluation and Monitoring Project (CREMP)

Coral reef ecosystems worldwide face unprecedented threats from a confluence of global and local stressors, including rising ocean temperatures, ocean acidification, pollution, and overfishing. Understanding the health and trends of these critical marine habitats is paramount for effective conservation and management. The Florida Reef Tract, extending approximately 360 miles along the southeastern coast of Florida, represents a significant coral reef ecosystem within the United States. Since 1996, the Coral Reef Evaluation and Monitoring Project (CREMP) has served as a cornerstone of monitoring efforts on this reef tract, providing a long-term and broad-scale assessment of its condition.1 This report aims to provide a comprehensive overview of CREMP, elucidating its historical development, clearly defined objectives, the methodologies it employs to gather crucial data, and the significant findings it has yielded regarding the status and trends of Florida's invaluable coral reef resources. By examining these aspects, the report will highlight CREMP's vital role in advancing our understanding of coral reef ecosystems and informing conservation strategies in the face of mounting environmental pressures.

1.2. Understanding CREMP: History, Objectives, and Regional Scope:

The Coral Reef Evaluation and Monitoring Project (CREMP) was initiated in 1996 within the Florida Keys, marking the beginning of a long-term commitment to understanding and protecting this vital ecosystem.2 This initial phase of CREMP was established as part of the Florida Keys National Marine Sanctuary's Water Quality Protection Program (WQPP), highlighting an early recognition of the interconnectedness between water quality and coral reef health.2 Three years later, in 1999, CREMP expanded its reach to include the reefs of the Dry Tortugas, further broadening its spatial coverage and the scope of its monitoring efforts.2 The most recent expansion occurred in 2003 with the establishment of the Southeast Florida Coral Reef Evaluation and Monitoring Project (SECREMP), which focuses on the reefs along the southeastern Florida coast.2 The initial funding for CREMP in the Florida Keys was provided by the Environmental Protection Agency (EPA) through the Water Quality Protection Program, underscoring the federal government's early investment in this critical monitoring

endeavor.2 In the Dry Tortugas, annual surveys of 12 CREMP sites are supported through a cooperative agreement between the National Park Service and the Florida Fish and Wildlife Conservation Commission (FWC), illustrating the collaborative nature of the project.2 Funding for SECREMP, which involves the survey of 22 CREMP sites in southeast Florida, is provided by the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program and the Florida Department of Environmental Protection, with Nova Southeastern University conducting the surveys in collaboration with FWC.2 This phased expansion across different regions of Florida's coral reefs indicates an increasing awareness of the need for comprehensive and spatially extensive monitoring to capture the complex dynamics of these ecosystems. The diverse array of funding sources from federal, state, and non-governmental entities underscores the widespread recognition of CREMP's importance to various institutions involved in marine research and conservation.



The primary objective of CREMP is to meticulously monitor the status and trends of selected coral reefs along Florida's Coral Reef, extending from Martin County in the north to the Dry Tortugas in the west, with the notable exclusion of Biscayne National Park and the Marquesas.[2] A core aim of the project is to document both the short-term fluctuations and the long-term transformations occurring within these vital benthic communities.[2] The data collected through CREMP is specifically intended to assist resource managers in their efforts to understand, protect, and ultimately restore the living marine resources found within the Florida Keys National Marine Sanctuary.[4] To achieve this, CREMP seeks to determine the overall net changes in key indicators such as stony coral percent cover and the richness of stony coral species, as well as other measurable parameters that characterize the health and composition of the reef community.[4] The program's design, with its broad spatial coverage and commitment to repeated sampling over time, is crucial for detecting changes occurring at the scale of the entire ecosystem.[4] These clearly defined objectives demonstrate CREMP's strong focus on providing the long-term, scientifically robust data necessary to inform effective management and conservation strategies for Florida's coral reefs. The emphasis on tracking multiple ecological metrics across a wide geographic area reflects a holistic approach to monitoring the complex changes within these dynamic ecosystems.

CREMP's monitoring efforts are strategically divided into three primary regions, each with its own distinct characteristics and history of monitoring. The Florida Keys region, initiated in 1996, encompasses 40 reef sites stretching from Carysfort Reef off Key Largo to Sand Key in Key West.[2] This region was specifically designed to document the status of reefs located within five of the nine EPA Water Quality Segments within the Florida Keys National Marine Sanctuary.[15] The Dry Tortugas region, established in 1999, includes 12 monitoring sites located within Dry Tortugas National Park and the adjacent Tortugas Northern Ecological Reserve.[2] These sites were selected to

represent the diverse array of coral reef habitats found in the Dry Tortugas, some of which are unique to this region of Florida's Coral Reef.[6] The Southeast Florida region, known as SECREMP, began its monitoring in 2003 and currently includes 22 reef sites located between Martin County and the northern boundary of Biscayne National Park.[2] Collectively, the spatial effort of CREMP spans over 70 monitoring sites along the entirety of Florida's Coral Reef, excluding Biscayne National Park and the Marquesas.[2] Within the Florida Keys, monitoring sites are strategically stratified based on both the subregion (Upper, Middle, and Lower Keys, defined by their geological and hydrological characteristics) and the type of reef habitat, including nearshore hardboflom, patch reefs, shallow forereefs, and deep forereefs.[15] This stratification ensures adequate representation of the various reef environments present in the Keys. The Dry Tortugas monitoring includes a variety of habitats, such as high-relief pinnacle reefs and spur and groove formations, supporting diverse benthic assemblages, as well as shallow stands of coral species listed under the Endangered Species Act.[6] While most individual sites in the Dry Tortugas were chosen to address specific research or management objectives, together they provide a general assessment of benthic habitat condition in the area.[6] SECREMP's focus on the northernmost extent of the Florida Reef Tract provides critical data on reef health in a region facing unique environmental pressures.[2] This regional approach allows CREMP to effectively assess reef health across different environmental gradients and within various management zones along Florida's extensive coral reef ecosystem. The careful selection of diverse habitats within each region ensures a comprehensive understanding of the ecological dynamics at play.

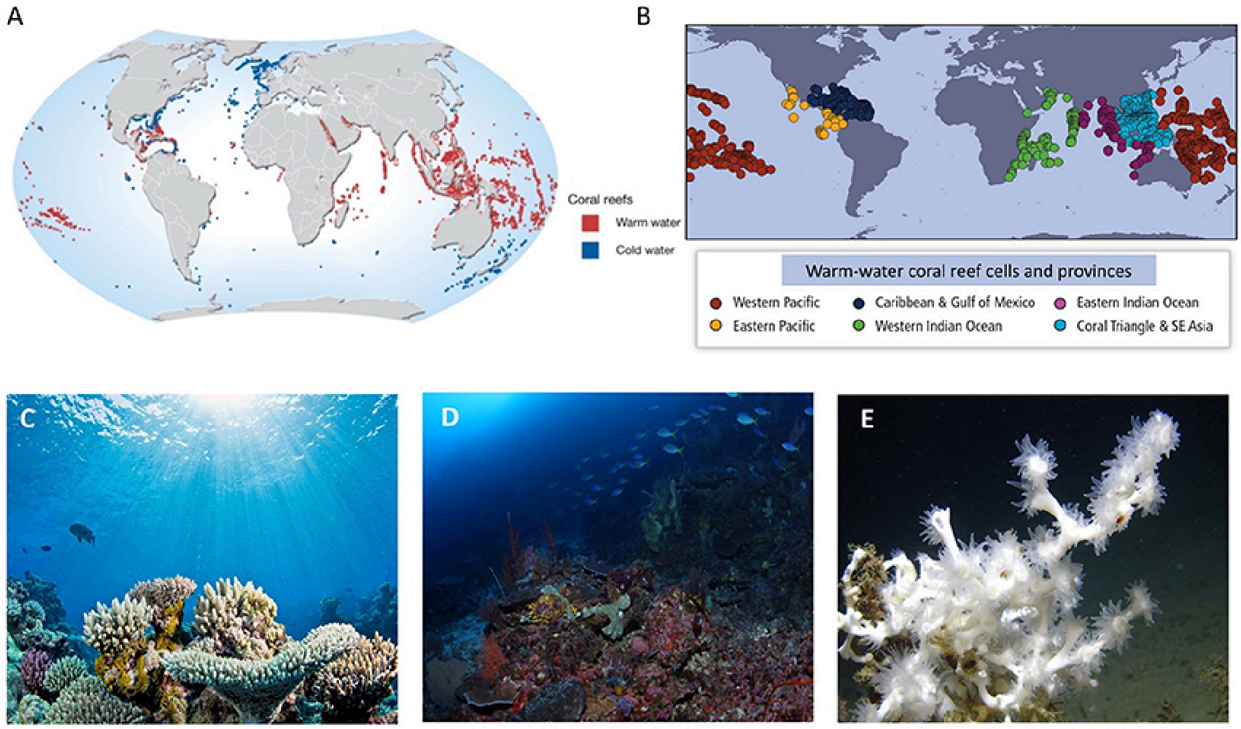
1.3. CREMP's Monitoring Methodologies: Evolution and Current Practices:

CREMP's approach to monitoring coral reefs has evolved over time, reflecting advancements in scientific understanding and the need to address emerging threats. Historically, CREMP employed three primary survey methods at each monitoring station to gather comprehensive data on the reef ecosystem.16 These included a video survey, which aimed to estimate the percent cover of various benthic organisms along three parallel transects, providing a visual record of the reef substrate.16 Additionally, a bio-eroding sponge survey was conducted to assess the abundance and distribution of these organisms, which play a significant role in reef dynamics.16 The third major survey was a coral species inventory, which focused on quantifying the richness of coral species present, noting the presence or absence of diseases affecting corals, and recording the abundance of long-spined sea urchins (Diadema antillarum) within the defined boundaries of the monitoring station.16 These historical methods relied on underwater videography along fixed transects to capture the overall benthic composition 9, complemented by timed inventories to specifically identify and count coral species.9 The inclusion of data on long-spined sea urchins was important due to their role as grazers and their susceptibility to mass mortality events that can impact reef health.16 This suite of historical methods provided a broad overview of the benthic community structure and the health status of the dominant reef organisms.

In 2011, CREMP implemented significant modifications to its survey methodologies to enhance the program's ability to assess changes in coral populations and to improve the efficiency of data collection.[16] The video survey for benthic cover was replaced with a method utilizing still photographs taken along a single, centered transect. This change was based on statistical analysis that indicated similar results could be obtained with a reduced sampling effort for percent cover assessment.[16] The coral species inventories were also replaced by more detailed coral and octocoral demographic surveys, which are conducted on the first 10 meters of the center transect in the Florida Keys and Dry Tortugas, and along the entire 22-meter length of the transect in SECREMP.[16] These demographic surveys involve identifying, measuring (corals ≥ 4 cm in Florida Keys/Dry Tortugas, ≥ 2 cm in Southeast Florida), and assessing the condition of individual coral colonies, including observations of mortality, bleaching, disease, or predation.[16] Since 2018, the protocol was further refined to include the enumeration of all coral colonies smaller than 4 cm in size, providing valuable data on juvenile coral populations and recruitment.[16] The bio-eroding sponge survey was discontinued and replaced with a demographic survey focusing on *Xestospongia muta*, the giant barrel sponge. This survey tracks individual sponge colonies to monitor their survival, growth, and population dynamics, providing information on density, size classes, and the prevalence of any malignant conditions.

For CREMP in the Florida Keys, this survey is conducted at 11 deep forereef sites along three 22m x 1m belt transects at two stations per site, while in SECREMP, it occurs along the same 22x1m belt transect as the coral demographic survey at all 22 sites.[16] Additionally, octocoral demographic surveys were introduced to quantify the abundance of all octocoral species and to collect demographic information on target species within the same transects used for stony coral surveys. Colonies of any size are recorded, their maximum height is measured, and target colonies are visually assessed for overall health.[16] Complementing these biological surveys, CREMP also conducts long-term temperature monitoring at all its active monitoring sites. Since 2002, HOBO Water Temp Pro v2 loggers have been deployed to record water temperatures on an hourly basis, providing a high-resolution, continuous temperature record that is crucial for understanding the environmental context of the biological changes observed.[1] In addition to these core methods, CREMP has also historically utilized underwater mapping, still photographs, and the collection of coral tissue and mucus samples for specific research purposes, such as investigating the impacts of black band disease.[17]

The rationale behind CREMP's monitoring methods is rooted in the need to identify the ecological processes that drive changes in coral populations and to test specific hypotheses regarding the responses of Florida's coral reef communities to both periodic disturbances and chronic environmental stressors.[16] The methodological modifications implemented in 2011 were aimed at providing a more detailed and ecologically relevant assessment of the benthic community while also enhancing the efficiency of the survey efforts. The decision to replace video surveys with still photographs and to reduce the number of transects for percent cover assessment was supported by statistical analyses that confirmed the reliability of a single transect in capturing representative data.[16] The shift from general coral species inventories to comprehensive demographic surveys allows for a more in-depth understanding of changes in coral reef community composition, particularly with the inclusion of octocoral and giant barrel sponge surveys.[16] These demographic surveys enhance the program's ability to identify the underlying processes contributing to coral declines or recoveries, such as changes in population density and size structure, the status of juvenile coral recruitment, the prevalence of conditions leading to mortality, and the role of chronic stressors.[16] The addition of octocoral surveys was driven by the recognition that octocorals are integral components of Caribbean reef communities, often occurring in high abundance and exhibiting rapid growth rates, making them valuable indicators of overall reef condition.[16] The implementation of the *Xestospongia muta* survey reflects the ecological importance of sponges in reef ecosystems and the susceptibility of this particular species to similar environmental stressors as corals, thus serving as another useful indicator of reef health.[16] The inclusion of juvenile coral tallies in 2018 was a significant addition to help determine if corals are successfully recruiting to the reef, a critical factor for long-term reef recovery.[16] Notably, the CREMP demographic survey protocols share similarities with those developed for the Atlantic and Gulf Rapid Reef Assessment (AGRRA), which facilitates the comparison of CREMP data with other reef monitoring programs across the region.[16]



1.4. Key Metrics in Coral Reef Monitoring: The Role of CREMP Data:

Several key metrics are fundamental to assessing the health and status of coral reef ecosystems. These metrics provide quantitative measures of different aspects of the reef community and are essential for tracking changes over time and understanding the impacts of various stressors. CREMP's long-term monitoring efforts provide valuable data on many of these crucial indicators.
Stony coral percent cover, defined as the proportion of a reef area covered by live stony corals, is a foundational metric in coral reef monitoring.[3] This metric is significant because stony corals are the primary reef-building organisms, and their abundance directly influences the structural complexity of the reef, which in turn provides habitat for a multitude of other marine species.[3] CREMP utilizes photographic surveys, employing point count methods on still images captured along transects, to estimate the percent cover of stony corals at its monitoring sites.[16]

Long-term data collected by CREMP has revealed significant declines in stony coral cover in the Florida Keys since the program's inception in 1996. These declines have been aflributed to a combination of factors, including thermal stress events, coral diseases, and the physical impacts of hurricanes.[3] Notably, CREMP data documented the largest one-year drop in stony coral cover in 2015, a decrease of 0.82% from the previous year, which was linked to a massive coral bleaching event resulting from record warm ocean temperatures.[3] This continuous monitoring of stony coral percent cover by CREMP provides critical evidence of the degradation of Florida's reefs and the profound impacts of major environmental disturbances. The data serves as an essential baseline for tracking long-term trends in reef health and for evaluating the effectiveness of conservation and restoration initiatives.

Coral species richness, which refers to the number of different coral species present within a defined area, is another critical metric for assessing the biodiversity and potential resilience of a coral reef ecosystem.[4] A higher diversity of coral species often indicates a more complex and potentially more resilient ecosystem, as different species may exhibit varying tolerances to environmental stressors.[27] Historically, CREMP collected data on coral species richness through its coral species inventory surveys.[16] Analysis of CREMP data has shown declines in the mean species richness observed in the Florida Keys, indicating a potential loss of biodiversity within the reef system.[26] CREMP's objectives include determining the overall net increase or decrease in stony coral species richness over time, highlighting the program's commitment to tracking changes in this important metric.[4] The long-term data on coral species richness collected by CREMP is vital for understanding the shifts in the biodiversity of Florida's reefs, which has significant implications for the overall health and long-term viability of the ecosystem. Declines in species richness can signal a reduction in functional diversity, potentially making the reef less able to withstand and recover from future disturbances.

Octocoral density, which measures the number of octocoral colonies per unit area, is increasingly recognized as a significant metric in coral reef monitoring.[16] Octocorals, also known as soft corals, sea fans, sea rods, and sea whips, play important roles in reef ecosystems by contributing to habitat structure and biodiversity.[38] In some disturbed environments, octocorals may exhibit competitive advantages over stony corals, leading to changes in their relative abundance.[3] CREMP currently collects detailed metrics and demographic data on octocorals, including maximum height, condition, and signs of mortality.[16] Notably, CREMP findings indicate a steady increase in the cover of octocorals in the Florida Keys since 1996, a period that has also seen a decline in stony coral cover.[3] CREMP data can be utilized to examine the density of

various octocoral species across different monitoring stations and to track changes in their density over extended periods.[25] This information is crucial for understanding the shifting dynamics of Florida's reefs. The observed increase in octocoral cover may suggest a transition towards a different type of reef ecosystem, potentially with altered ecological functions. Further analysis of CREMP data could also help to reveal potential correlations between octocoral density and environmental factors such as water temperature and water quality.[25]

Live tissue area, which represents the actual surface area of living coral tissue on a colony or within a given reef area, is a direct indicator of coral health and its capacity for essential biological functions like growth and reproduction.[16] While CREMP does not directly measure live tissue area in square centimeters, the program collects several metrics for stony corals that can be used to infer changes in this parameter. These include maximum diameter, maximum height, and detailed assessments of mortality and condition.[16] Additionally, CREMP employs photographic analysis to estimate the percent cover of live stony coral tissue across monitoring transects.[16] The demographic surveys conducted by CREMP involve recording the amount of mortality on each identified coral colony, which inherently implies an assessment of the remaining living tissue.[16] By analyzing these data, researchers can determine differences in the living tissue area of stony corals between various monitoring sites and track how this vital aspect of coral health changes over time.[25] Although not a direct measurement of surface area, the combination of these metrics provides a robust understanding of the health and vitality of stony corals within the Florida Reef Tract.

1.5. Factors Influencing Coral Reef Health: A CREMP Perspective:

The health of coral reef ecosystems is influenced by a complex interplay of environmental factors. CREMP's long-term monitoring has provided valuable insights into the role of several key factors impacting Florida's coral reefs.
Water temperature plays a critical role in coral health, and corals are known to be highly sensitive to even small changes in temperature.[1] Temperatures that deviate from the normal range can lead to stress responses such as coral bleaching, reduced growth rates, reproductive problems, increased susceptibility to diseases, and ultimately, mortality.[1] Recognizing the importance of this factor, CREMP has maintained a long-term temperature monitoring program at all its active sites since 2002.[1] This program utilizes HOBO Water Temp Pro v2 loggers that record water temperatures on an hourly basis, providing a detailed and continuous record.[19] These data are crucial for understanding the thermal environment experienced by the corals at CREMP's monitoring locations. Historical records and CREMP data indicate that Florida's Coral Reef has been affected by six mass coral bleaching events since 1987,

with particularly high coral mortality observed during the global bleaching events of 1997/1998 and 2014/2015.[19] Furthermore, corals at the northern extent of their distribution in Florida are also vulnerable to periods of cold water temperatures during the winter months, which can also cause significant stress and mortality.[19] The pairing of CREMP's long-term temperature data with its extensive coral survey data is essential for scientists to gain a befler understanding of how temperature stress is affecting coral populations in Florida and to differentiate temperature-related impacts from those caused by other environmental factors.

Water quality is another crucial determinant of coral reef health, and poor water quality, characterized by factors such as excess nutrients, increased sedimentation, and the presence of various pollutants, can have significant negative impacts on coral reefs.[4] The fact that funding for CREMP in the Florida Keys is supported by the EPA Water Quality Protection Program (WQPP) highlights the recognized link between water quality and the health of these coral ecosystems.[2] Within the Florida Keys National Marine Sanctuary, CREMP's coral reef monitoring efforts are integrated with programs that also monitor seagrass habitats and water quality, reflecting a holistic approach to understanding the dynamics of the marine environment.[4] CREMP data plays a vital role in the WQPP by providing information on the status and trends of coral reef habitats, which helps researchers and resource managers understand the relationship between coral health and the surrounding water quality.[64] While the provided snippets do not detail specific water quality data collected directly by CREMP, they emphasize the program's integral role within the broader context of water quality monitoring efforts in the region. Further investigation into CREMP's publications and reports may yield more specific information on water quality parameters that have been examined in relation to coral health.[2]

Pollution, originating from various land-based and marine sources, poses a significant threat to coral reef ecosystems.[57] This includes sedimentation, which can smother corals and interfere with their ability to feed and reproduce, often resulting from coastal development and runoff.[58] Excess nutrients, primarily from agricultural and residential fertilizers and sewage discharge, can lead to harmful algal blooms that outcompete corals for space and light.[58] Pathogens from inadequately treated wastewater can also cause diseases in corals, particularly when they are already stressed by other environmental conditions.[58] Toxic substances, such as heavy metals and pesticides found in industrial and agricultural runoff, can impair coral reproduction and growth.[58] Furthermore, trash and microplastics that enter the marine environment can cause physical damage to corals, block sunlight, and potentially introduce harmful chemicals into the food web.[58] While CREMP's primaryfocus is on monitoring the biological components of the reef, the data it collects on coral health, disease prevalence, and benthic community composition can provide valuable insights into the ecological impacts of various forms of pollution on these sensitive ecosystems.

Fishing pressure, both from overfishing and destructive fishing practices, can also significantly influence the health of coral reefs.[57] Overfishing can disrupt the delicate balance of the reef's food web, for example, by reducing the populations of herbivorous fish that play a crucial role in controlling the growth of algae on corals.[58] Destructive fishing methods, such as blast fishing (using explosives to kill fish), can cause direct physical damage to the coral structures, leading to habitat destruction and fragmentation.[58] While CREMP does not directly monitor fishing activities, the program's long-term data on coral cover, species diversity, and the abundance of other benthic organisms can indirectly reflect the impacts of fishing pressure on the overall health and resilience of the Florida Reef Tract.

Climate change represents the overarching global threat to coral reef ecosystems, primarily through increased ocean temperatures and ocean acidification.[57] Rising ocean temperatures are the primary driver of coral bleaching, a stress response where corals expel their symbiotic algae, leading to the loss of color and a reduction in energy production.[19] If bleaching events are severe or prolonged, they can result in widespread coral mortality.[19] Ocean acidification, caused by the absorption of excess carbon dioxide from the atmosphere into the ocean, leads to a decrease in seawater pH and a reduction in the availability of carbonate ions, which are essential for corals to build and maintain their calcium carbonate skeletons.[58] This process can slow coral growth, weaken their skeletal structures, and make them more vulnerable to erosion and damage.[58] Additionally, climate change is associated with other impacts such as sea-level rise, increased frequency and intensity of storms, and altered ocean circulation paflerns, all of which can further stress and damage coral reef ecosystems.[58] CREMP's long-term monitoring data, particularly its records of coral bleaching events, changes in coral cover, and shifts in species composition over time, provide critical evidence of the impacts of climate change on Florida's coral reefs. This information is essential for understanding the scale and magnitude of these threats and for informing strategies to enhance the resilience of these valuable ecosystems.

1.6. Identifying Early Warning Indicators of Coral Decline through CREMP:

Early detection of coral decline is crucial for implementing timely and effective conservation measures. CREMP's comprehensive monitoring program provides data on several established indicators that can serve as early warnings of stress and potential decline in both stony corals and octocorals.

Percent recent mortality (PRM) of stony corals is a key indicator that reflects tissue death occurring in the days to months preceding a survey.[72] CREMP's demographic surveys record the amount of mortality on individual coral colonies, allowing for the calculation of PRM at different monitoring sites.[16] Based on extensive data from Florida reefs, benchmark PRM levels have been proposed to help identify conditions of concern. PRM levels above 1.0% can be considered early warning signs of degrading conditions, while values exceeding 2% indicate increasingly stressful environments.[72] Significant increases in PRM, such as those observed by CREMP following extreme temperature events, can signal the potential for major coral mortality.[72]

The prevalence of coral diseases is another significant early warning indicator. CREMP's health assessments of stony corals include documenting various conditions such as tissue loss, color loss, discoloration, and growth anomalies.[16] Increases in the incidence and severity of these diseases can indicate that corals are under stress and their health is declining.[73] CREMP's long-term data allows for the tracking of disease trends over time, providing valuable information on the health of coral populations.[2]

Coral bleaching, the paling or whitening of corals due to the expulsion of their symbiotic algae, is a well-established indicator of thermal stress.[16] CREMP surveys include observations of bleaching prevalence and severity, providing crucial data on the impact of elevated water temperatures on Florida's reefs.[16] The frequency and extent of bleaching events recorded by CREMP serve as important early warnings of climate change impacts on these sensitive ecosystems.[19]

Changes in coral recruitment rates, as indicated by the number of juvenile corals observed during surveys, can provide insights into the future health and recovery potential of a reef.[16] Since 2018, CREMP has included the enumeration of all coral colonies smaller than 4 cm in its surveys, allowing for the assessment of juvenile coral abundance and distribution.[16] A decline in recruitment rates can be an early warning sign that a reef's ability to recover from disturbances is compromised.

Similar to stony corals, octocorals also exhibit stress responses that can serve as early warning indicators. CREMP's octocoral surveys include assessments of their condition, noting signs such as tissue loss and bleaching.[16] Changes in the health status of octocorals can provide additional insights into the overall condition of the reef community and whether stressors are affecting different taxonomic groups similarly.[16]

CREMP's long-term and comprehensive data collection on these various indicators for both stony corals and octocorals makes it a powerful tool for identifying early warning signs of coral decline within the Florida Reef Tract. By tracking trends in PRM, disease prevalence, bleaching, recruitment, and octocoral health, scientists and managers can gain valuable lead time to understand the nature and extent of reef degradation and to implement appropriate conservation and management actions.

1.7. Predicting Coral Reef Futures: Models and CREMP's Role:

Predicting the future evolution of coral reefs under the influence of climate change and other stressors is a critical area of research. Various types of models are being developed to simulate coral reef dynamics and to forecast their responses to different environmental scenarios.75 These models range from ecological models that focus on species interactions and environmental drivers to evolutionary models that incorporate the capacity of corals and their symbionts to adapt to changing conditions.77 Some models specifically examine the role of symbiont shuffling (the shift in dominant symbiont types within a coral host) and the evolution of thermal tolerance in determining coral survival under warming oceans.77 Other models consider the influence of larval dispersal paflerns and the connectivity between different reefs in facilitating or hindering adaptation and recovery.78 Over longer timescales, models using approaches like cellular automata and fuzzy logic are employed to simulate the geological and ecological evolution of reef structures.76
The extensive long-term data collected by CREMP provides a valuable resource for both validating and refining these predictive models.[7] CREMP's detailed records on coral cover, species composition, and health assessments over nearly three decades can be used to test how well model predictions align with real-world observations.[7] For example, CREMP's hourly temperature data, which spans many years across different reef regions in Florida, can be integrated into models to improve the accuracy of predictions regarding coral bleaching events and their subsequent impacts on coral mortality and community structure.[1] Furthermore, CREMP has documented significant shifts in species dominance on Florida's reefs, such as the decline of once-dominant *Acropora* species and the increase in more stress-tolerant species like *Porites*.[16] This real-world data on species-specific responses to various stressors can be used to inform and calibrate the parameters within predictive models, making them more accurate in forecasting future reef community compositions under different climate change scenarios.[77] By comparing the trends observed in CREMP's long-term dataset with the outputs of various coral reef evolution models, researchers can assess the strengths and limitations of these models and work towards developing more robust and reliable tools for predicting the future of coral reef ecosystems. This iterative process of model validation and refinement using real-world data is crucial for enhancing our ability to anticipate the impacts of environmental change and to inform effective conservation and management strategies for coral reefs.

1.8. CREMP in a Global Context: A Comparative Analysis:

The Coral Reef Evaluation and Monitoring Project (CREMP) is one of many significant coral reef monitoring programs operating around the world, each contributing valuable data and insights into the health of these critical ecosystems. Comparing CREMP with other major initiatives highlights its unique contributions and places it within a broader global context. One prominent global program is the NOAA Coral Reef Watch (CRW), which utilizes satellite-based measurements of sea surface temperature and related parameters to monitor thermal stress and predict coral bleaching events on a global scale.[83] While CRW provides broad-scale, near real-time information on bleaching risk, CREMP offers detailed, in-situ biological monitoring of specific reef sites within the Florida Reef Tract, providing a finer-scale understanding of the ecological impacts of various stressors, including but not limited to temperature.[83]

The Australian Institute of Marine Science (AIMS) conducts a Long-Term Monitoring Program (LTMP) on the Great Barrier Reef, employing methods such as manta tow surveys for broad-scale assessments and fixed site surveys using photography and visual counts for detailed monitoring of coral and fish communities.[84] Similar to CREMP, AIMS' LTMP relies on long-term data collection at fixed sites to detect changes in reef condition indicators over time.[84] Both programs utilize transect surveys, photographic documentation, and demographic assessments to gather crucial data.[16]

In the United States, the National Coral Reef Monitoring Program (NCRMP) provides an integrated ecosystem perspective on coral reef status by monitoring climate, fish, benthic organisms, and socioeconomic indicators across all U.S. states and territories with coral reefs.[87] NCRMP employs a stratified random sampling design to provide representative data at regional and jurisdictional scales.[87] While NCRMP has a broader geographic scope than CREMP, which focuses specifically on Florida, both programs contribute to a national understanding of coral reef health.[87]

The Global Coral Reef Monitoring Network (GCRMN) is a worldwide network that compiles data from numerous monitoring programs, including potentially CREMP, to report on the status and trends of coral reefs globally.[90] GCRMN's reports provide a comprehensive overview of global coral reef health, highlighting major trends in coral cover and bleaching.[90] CREMP's long-term data likely contributes to these global assessments, providing a valuable regional perspective from the Florida Reef Tract.

The Allen Coral Atlas utilizes high-resolution satellite imagery combined with advanced analysis techniques to map and monitor coral reefs worldwide, including the detection of coral bleaching events.[94] While this program offers a broad spatial view of reef health, CREMP's in-situ monitoring provides ground-truthing data and detailed ecological information that complements satellite-based observations.[94]

CREMP's long tenure, since its inception in 1996, stands as a significant strength, providing an exceptionally long-term dataset for analyzing trends and changes in Florida's coral reefs.[1] Its specific regional focus on the Florida Reef Tract allows for the development of detailed insights into the unique ecological dynamics and challenges facing this particular ecosystem.[2] Furthermore, the integration of CREMP data into the Florida Keys National Marine Sanctuary's Water Quality Protection Program demonstrates a strong link between the monitoring program and direct management applications.[3] While some global programs like NOAA CRW focus on broad-scale thermal stress monitoring, CREMP provides critical in-situ biological data that is essential for understanding the complex responses of coral reef communities to a multitude of interacting stressors. In contrast to the global scope of GCRMN, CREMP offers a deep and continuous record for a specific and important reef region. This comparative analysis underscores the value of CREMP as a well-established regional monitoring program with a long history, detailed methodologies, and strong ties to conservation and management efforts, making it a crucial component of the global endeavor to understand and protect coral reef ecosystems.

1.9. Conclusion: Significance of CREMP and Recommendations for Future Directions:

The Coral Reef Evaluation and Monitoring Project (CREMP) has played a vital and enduring role in providing long-term, high-quality data on the status and trends of Florida's precious coral reef ecosystems since its inception in 1996. Over the past nearly three decades, CREMP's meticulous monitoring efforts have documented significant changes, including concerning declines in stony coral cover and species richness, alongside an increase in octocoral abundance. These trends underscore the profound impacts of thermal stress, disease outbreaks, and other environmental stressors on the Florida Reef Tract. The valuable data collected by CREMP has been instrumental in identifying early warning indicators of coral decline, such as percent recent mortality, disease prevalence, and bleaching events, providing crucial information for timely conservation interventions. Furthermore, CREMP's extensive dataset offers an invaluable resource for validating and refining predictive models that aim to forecast the future evolution of coral reefs under various climate change scenarios. When viewed within the broader context of global coral reef monitoring programs, CREMP stands out for its long tenure, its specific focus on the ecologically significant Florida Reef Tract, and its strong integration with regional water quality protection and marine sanctuary management efforts.

To further enhance the impact and effectiveness of CREMP in the coming years, several recommendations can be considered. Continued long-term monitoring remains paramount to track ongoing changes in reef health and to assess the efficacy of current and future conservation strategies. Strengthening the integration of

CREMP's biological data with comprehensive water quality monitoring efforts would provide a more holistic understanding of the combined impacts of multiple stressors on coral reefs. Leveraging CREMP's rich dataset to further refine and validate predictive models will improve our ability to anticipate future reef states under different climate scenarios and inform long-term management decisions. Exploring opportunities for increased collaboration and data sharing with other regional, national, and global monitoring programs would enhance the overall understanding of coral reef dynamics and facilitate the development of more effective conservation approaches. Investigating the potential application of emerging technologies, such as remote sensing techniques and artificial intelligence-assisted image analysis, could enhance the efficiency, spatial scope, and taxonomic resolution of CREMP's monitoring efforts. Focused research on understanding the ecological drivers and implications of the observed increase in octocoral abundance is warranted to befler interpret the long-term changes occurring on Florida's reefs. Finally, strengthening outreach and communication efforts to ensure that CREMP's valuable data and findings are readily accessible and effectively communicated to a wide range of stakeholders, including policymakers, resource managers, scientists, and the general public, is crucial for fostering informed decision-making and promoting the conservation of Florida's irreplaceable coral reef ecosystems.

Region Name	**Initiation Year**	**Number of Monitoring Sites**	**Spatial Coverage**	**Key Habitats Monitored**	**Primary Funding Sources**	**Conducting Agency**
Florida Keys	1996	40	Carysfort Reef to Sand Key	Nearshore hardboflom, patch reefs, shallow forereefs, deep forereefs	EPA Water Quality Protection Program	FWC
Dry Tortugas	1999	12	Dry Tortugas National Park and Tortugas Ecological Reserve North	High-relief pinnacle reefs, spur and groove reefs, shallow stands of ESA-listed corals, patch reefs with ESA-listed corals	National Park Service	FWC

Southeast Florida	2003	22	Martin County to northern boundary of Biscayne National Park	Primarily shallow and deep forereefs	NOAA Coral Reef Conservation Program, Florida Department of Environmental Protection	Nova Southeastern University in collaboration with FWC

Monitoring Period	**Survey Type**	**Historical Methods**	**Current Methods**	**Key Parameters Monitored**
Historical (pre-2011)	Benthic Cover	Video survey along three parallel transects	Still photographs along a single centered transect	Percent cover of stony corals, octocorals, sponges, macroalgae
Historical (pre-2011)	Coral Health & Diversity	Coral species inventory survey	Coral and octocoral demographic surveys	Stony coral species richness, presence of disease, abundance of long-spined sea urchins, abundance and condition of individual coral and octocoral colonies, size of corals
Historical (pre-2011)	Bio-eroding Sponges	Bio-eroding sponge survey	*Xestospongia muta* demographic survey	Abundance and distribution of bio-eroding sponges

Current (since 2011)	Giant Barrel Sponges	Not monitored	*Xestospongia muta* demographic survey	Survival, growth, population dynamics, density, size class, prevalence of malignant conditions
Current (since 2011)	Juvenile Corals	Not systematically quantified	Enumeration of all colonies < 4 cm	Abundance of juvenile corals
Current (since 2011)	Temperature	Not continuously monitored at all sites	Hourly temperature monitoring using HOBO loggers at all active sites	Water temperature

Metric	**Significance in Coral Reef Monitoring**	**How CREMP Data is Collected**	**Key CREMP Findings Related to the Metric**
Stony Coral Percent Cover	Reflects abundance of reef-building organisms and habitat complexity; indicator of overall reef health	Photographic surveys with point counts on transect images	Significant decline in Florida Keys since 1996 (53.8% from 1996-2015); largest one-year drop in 2015 due to bleaching
Coral Species Richness	Indicates biodiversity and potential resilience of the ecosystem	Historically through coral species inventory surveys; currently through demographic surveys	Decline in mean species richness observed in the Florida Keys

Octocoral Density	Contributes to habitat structure and biodiversity; potential indicator of shifts in community composition	Octocoral demographic surveys including abundance and size measurements	Steady increase in octocoral cover in the Florida Keys since 1996 while stony corals declined
Live Tissue Area	Direct measure of coral health and capacity for growth and reproduction	Photographic analysis for percent cover; demographic surveys record mortality and condition of individual colonies	Data used to determine differences between sites and track changes over time, indicating overall health trends

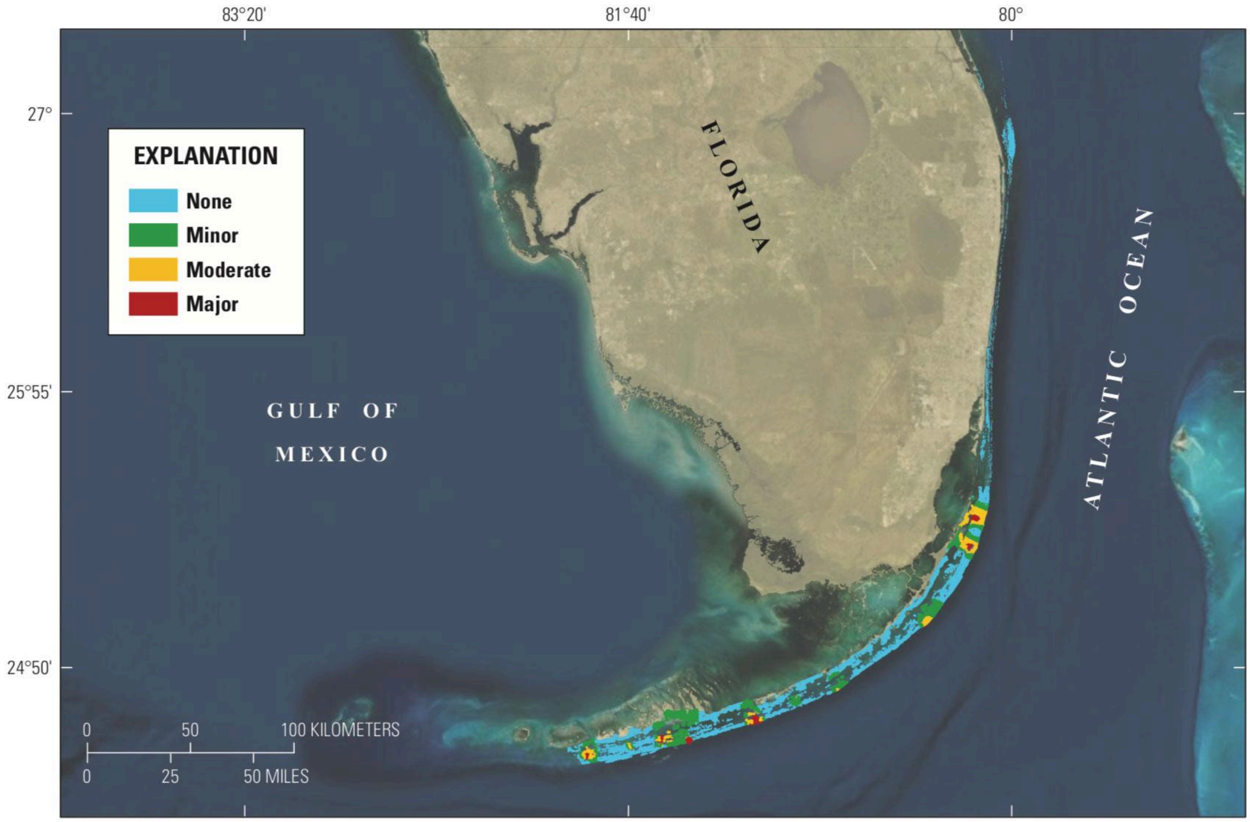
Progra m Name	**Geographi c Focus**	**Key Methodolog ies**	**Primary Parameter s Monitored**	**Tempor al Scale**	**Link to Manageme n t/Conserva t ion**
CREMP	Florida Reef Tract (Florida Keys, Dry Tortugas, Southeast Florida)	Transect surveys, still photography , demographi c surveys (stony corals, octocorals, giant barrel sponges), hourly temperatur e monitoring	Stony coral percent cover, coral species richness, octocoral density, live tissue area (inferred), coral condition, juvenile coral abundance, water temperature	Long-term (since 1996)	Strong integration with Florida Keys National Marine Sanctuary's Water Quality Protection Program and other management efforts in Florida

NOAA Coral Reef Watch	Global	Satellite-based measurements	Sea surface temperature, SST anomalies, coral bleaching hotspots, degree heating weeks	Near real-time	Provides alerts and information to reef managers worldwide
AIMS LTMP	Great Barrier Reef, Australia	Manta tow surveys, fixed site surveys (photography and visual counts)	Coral cover, crown-of-thorns starfish abundance, coral bleaching, reef fish abundance, benthic community composition	Long-term (since 1985)	Informs management of the Great Barrier Reef Marine Park
NCRMP	U.S. states and territories with coral reefs	Stratified random surveys (in-situ diver surveys and structure-from-motion imagery)	Coral demographics, fish populations, climate variables, socioeconomic indicators	Since 2013	Provides data for national-scale assessments and informs policy and management
GCRMN	Global	Compilation of data from various monitoring programs	Hard coral cover, algal cover, coral bleaching	Since 1978	Provides global status reports on coral reef health and trends

Allen Coral Atlas	Global	Satellite imagery analysis	Coral reef extent, benthic habitat mapping, coral bleaching detection	Ongoing	Supports conservation and management through mapping and monitoring

1.10. CREMP's Methodological Approach to Coral Reef Assessment

CREMP employs a suite of detailed monitoring protocols designed to comprehensively assess the health and status of Florida's coral reefs.[14] The current methodologies encompass several key components, including photographic surveys, stony coral demographic assessments, octocoral demographic surveys, and monitoring of barrel sponge populations.[14] The photographic surveys are crucial for quantifying the percent cover of various benthic organisms. During these surveys, divers utilize



point-and-shoot cameras to capture images along the entire length of approximately 22-meter transects, meticulously following a plastic chain laid along the reef substrate.[14] These images are subsequently analyzed using specialized software, PointCount '99, where a grid of random points is overlaid on each photograph to identify and quantify the different benthic taxa present. This process generates precise estimates of the percent cover of corals, algae, sponges, and other reef inhabitants for each transect.[14] To complement this quantitative data, panoramic photographs are also taken at the offshore end of each transect. These panoramic images serve as a valuable visual record, documenting long-term changes in the overall reef structure and composition over time.[14]

In addition to the broad-scale assessment of benthic cover, CREMP conducts detailed demographic surveys focusing on both stony corals and octocorals. The stony coral demographic surveys are carried out on the initial 10 meters of each station transect in the Florida Keys and the Dry Tortugas, and along the entire 22-meter length in Southeast Florida.[14] Within a 0.5-meter corridor on either side of the transect line, all stony coral colonies meeting a minimum size threshold (≥ 4 cm in the Keys and Dry Tortugas, and ≥ 2 cm in Southeast Florida) are identified to species, their size is measured, and their overall health is evaluated.[14] This health assessment includes recording any signs of mortality, bleaching, disease, or predation observed on each colony.[14] Since 2018, smaller coral colonies (juveniles) less than 4 cm in size are also counted to gather important information on coral recruitment and population dynamics.[14] The presence of the branching fire coral (*Millepora alcicornis*) and the abundance of long-spined sea urchins (*Diadema antillarum*) are also noted within these survey areas.[14] The protocols employed for these stony coral surveys are designed to be consistent with those of the Atlantic and Gulf Rapid Reef Assessment (AGRRA), ensuring comparability of data across the wider Caribbean region.[14]

Octocoral demographic surveys are conducted at approximately half of the CREMP sites in the Florida Keys and at all monitoring sites in the Dry Tortugas and Southeast Florida.[14] These surveys are performed within the same transects used for the stony coral assessments. The primary goal is to quantify the abundance of all octocoral species present. For a subset of ecologically important or dominant target octocoral species, more detailed demographic information is collected, including their maximum height and assessments of their health, noting any signs of disease, damage, mortality, or other abnormalities.[14] Non-target octocoral species encountered are also tallied separately to provide a comprehensive understanding of the octocoral community.[14]

Finally, CREMP includes a specialized survey targeting the giant barrel sponge (*Xestospongia muta*), a significant component of many coral reef ecosystems. This survey involves tracking individual colonies of these large sponges to monitor their survival, growth rates, and overall population dynamics.[14] In the Florida Keys, this survey is conducted at the 11 deep forereef monitoring sites, utilizing three parallel 1-meter wide transects that run along the entire approximately 22-meter station length.[14] In Southeast Florida (SECREMP), the giant barrel sponge survey is integrated with the coral demographic survey, conducted along the same 22x1-meter belt transect.[14] During these surveys, researchers relocate each tagged sponge colony using underwater site maps and photographs, measure their dimensions, and record the presence of any signs of bleaching, disease, or predation.[14]

CREMP's methodological approach has evolved considerably since its inception. Initially, the program relied on underwater video surveys to estimate benthic cover along three parallel transects at each sampling station, accompanied by a coral species inventory that quantified coral species richness, the presence or absence of disease, and the abundance of long-spined sea urchins.[14] Over time, the program has incorporated new technologies and refined its techniques. Temperature loggers were first deployed at a subset of survey sites in 2002 to examine spatial and temporal variations in boflom temperatures.[26] A significant methodological shift occurred in 2011, driven by the need to improve the efficiency of data collection and to provide a more comprehensive assessment of the benthic community.[14] The video surveys were replaced with still photography and reduced from three transects to a single centered transect.[14] The traditional coral species inventories were superseded by the more detailed coral and octocoral demographic surveys, focusing on the first 10 meters of the center transect.[14] The bio-eroding sponge survey was discontinued and replaced with the fate-tracking survey of the giant barrel sponge (*Xestospongia muta*).[14]

Additional modifications have included surveys to document the abundance and cover of Clionid sponges and the tallying of juvenile coral recruits.[14] Furthermore, the protocols for recording injuries and diseases on coral colonies have been enhanced to provide a more detailed description of coral health conditions.[14]

The spatial design of CREMP's monitoring efforts is carefully structured to ensure representative sampling across the diverse reef habitats of Florida's Coral Reef. Within both Southeast Florida and the Florida Keys, each CREMP site typically consists of four distinct monitoring stations.[14] In the Dry Tortugas, the program encompasses 12 designated monitoring reefs.[11] Each monitoring station is delimited by permanent markers, usually stainless steel stakes epoxied into the reef framework, and typically measures approximately 2 meters in width and 22 meters in length.[14] These transects are generally oriented perpendicular to the shoreline to capture the different ecological zones that may exist from nearshore to offshore areas.[14] In the Florida Keys and the Dry Tortugas, surveyors follow a consistent protocol of proceeding from the offshore stake towards the inshore stake along the transect line.[14] In Southeast Florida (SECREMP), the orientation is from south to north along the transect.[14] To ensure accurate measurements of benthic cover and coral demographics, a plastic chain is often placed directly underneath the fiberglass transect tape, allowing it to follow the natural contours of the reef substrate.[14] In the Florida Keys, CREMP sites were originally established to represent three primary reef habitat types: patch reefs, shallow forereefs, and deep forereefs, providing a stratified approach to understanding reef health across different ecological seflings.[23] The shift from video to still photography in CREMP's methodology likely aimed to enhance the efficiency and precision of benthic cover assessments. While video surveys provide a continuous record of the transect, the analysis can be time-consuming.

Still photographs, coupled with software like PointCount, allow for a rapid and standardized quantification of benthic components. The inclusion of octocoral and barrel sponge surveys in the modified methodology indicates an expanded understanding of the reef ecosystem, moving beyond a primary focus on stony corals to incorporate other ecologically significant benthic organisms. The detailed spatial design of CREMP, with its permanently marked stations and standardized transect methods, is crucial for ensuring the repeatability and comparability of data collected over the long term.

This consistency is essential for accurately detecting trends in coral reef health and distinguishing these trends from natural year-to-year variability. The stratification of monitoring sites by habitat type further allows for a more nuanced analysis of reef health, taking into acount the inherent differences in ecological structure and function among different reef zones.

2. CREMP in a Global Context: A Comparative Analysis

The Coral Reef Evaluation and Monitoring Project (CREMP) is one of many significant initiatives dedicated to understanding and conserving coral reef ecosystems worldwide. Several other major global programs employ diverse methodologies and operate at various spatial scales to monitor the health of these critical habitats. The Global Coral Reef Monitoring Network (GCRMN) stands as a prominent international network operating under the International Coral Reef Initiative (ICRI).[28] Functioning through 10 regional nodes, the GCRMN aims to provide the most reliable scientific information on the status and trends of coral reefs globally, culminating in the influential "Status of Coral Reefs of the World" report.[28] Reef Check offers a contrasting approach by training citizen scientists to monitor reef health and coral bleaching using standardized belt transect methods across more than 100 countries.[33] The National Oceanic and Atmospheric Administration (NOAA) also plays a crucial role through its Coral Reef Watch (CRW) program, which utilizes a combination of remote sensing, modeled data, and in-situ observations to monitor and predict threats to coral reef environments on a global scale.[33] CRW provides near real-time satellite-derived products, such as the Bleaching Alert Area, Degree Heating Week (DHW), and HotSpot maps, which are vital for early warning of coral bleaching events.[35] The Allen Coral Atlas offers another technologically advanced approach, employing satellite imagery to map the world's coral reefs and monitor threats like bleaching and changes in water turbidity, providing valuable data on reef extent, composition, and health.[36] Regionally focused programs also contribute significantly, such as the Atlantic and Gulf Rapid Reef Assessment (AGRRA), which provides standardized protocols for coral reef monitoring specifically within the Wider Caribbean region [14], and the National Coral Reef Monitoring Program (NCRMP) in the United States, which monitors coral health using belt transects across U.S. states and territories.[30]

Comparing these programs reveals distinct methodologies, spatial scales, and reporting mechanisms. The GCRMN adopts an integrative approach, collecting and standardizing data from diverse monitoring programs worldwide through direct contact with data custodians or by utilizing databases and scientific literature.[28] This aggregated data is then subjected to rigorous quality checks to ensure consistency and reliability before being used in their global assessments.[28] Reef Check's methodology is centered on engaging citizen scientists in data collection using a globally standardized protocol, allowing for widespread monitoring with the data ultimately informing expert assessments.[33] NOAA CRW's strength lies in its utilization of satellite technology to provide a global early warning system for coral bleaching, offering frequent updates and alerts based on sea surface temperature anomalies.[35] The Allen Coral Atlas also leverages satellite imagery but focuses on creating detailed global habitat maps and monitoring changes in reef health indicators in near

real-time.[36] Regionally, AGRRA provides a standardized framework for data collection and assessment within the Caribbean, promoting comparability across different monitoring efforts.[14] NCRMP focuses its efforts on U.S. coral reefs, employing belt transect surveys and offering interactive data visualization tools to explore the status and trends of these ecosystems.[33] CREMP, in contrast, focuses specifically on Florida's Coral Reef, utilizing a combination of fixed monitoring sites and detailed photographic and demographic surveys.[11] The program reports its findings annually and makes data accessible through online repositories and interactive dashboards, providing detailed insights into the health of Florida's reefs.[10] Notably, CREMP's demographic survey protocols share similarities with AGRRA, facilitating comparisons within the broader Caribbean context.[14] Furthermore, CREMP's use of still photography for benthic cover assessment aligns with methods employed by other programs like the Hawaii Coral Reef Assessment and Monitoring Program (CRAMP).[41] Historically, CREMP's use of video transects mirrors techniques utilized by other monitoring and research programs in the Caribbean and Australia.[15] Research has indicated that image-based protocols, such as CREMP's current photographic method, tend to have higher repeatability and lower variability in benthic cover estimates compared to visual survey-based protocols like AGRRA and Point Intercept Transect (PIT).[42]

The global effort to monitor coral reefs is increasingly supported by the development and adoption of open-source tools and platforms. The Wildlife Conservation Society (WCS) and MERMAID (Marine Ecological Research Management Aid) provide a notable example of an open-source platform designed for coral reef data management, analysis, and sharing.[33] MERMAID utilizes the open-source database PostgreSQL for its backend infrastructure, enabling scalable data management and analysis.[43] CoralSoundExplorer is another valuable open-source tool, specifically designed for studying and monitoring coral reef soundscapes using machine learning techniques.[46] ReefCloud leverages the power of photography and artificial intelligence to track reef health across various global locations.[33] EarthToolsMaker has developed open-source artificial intelligence models aimed at enhancing the analysis of benthic imagery collected during coral reef monitoring efforts.[47] For data visualization and exploration, NOAA's NCRMP offers the NCRMP Data Visualization Tool, a GIS application built using ArcGIS that allows users to interact with benthic, fish, climate, and socioeconomic data related to U.S. coral reefs.[40] Recognizing the importance of data standardization and interoperability, the Global Coral Reef Monitoring Network

(GCRMN) is actively working towards adopting Darwin Core as a global data standard to facilitate the integration and comparison of data from diverse sources.[30] The comparison of global coral reef monitoring programs highlights a range of strategies tailored to different scales and objectives. Satellite-based programs like NOAA CRW and the Allen Coral Atlas offer broad spatial coverage, while citizen science initiatives such as Reef Check engage a wide network of volunteers. Regionally focused programs like CREMP, AGRRA, and NCRMP provide detailed, long-term data relevant to specific geographic areas and management needs. This diversity of approaches underscores the complexity of coral reef monitoring and the necessity of a

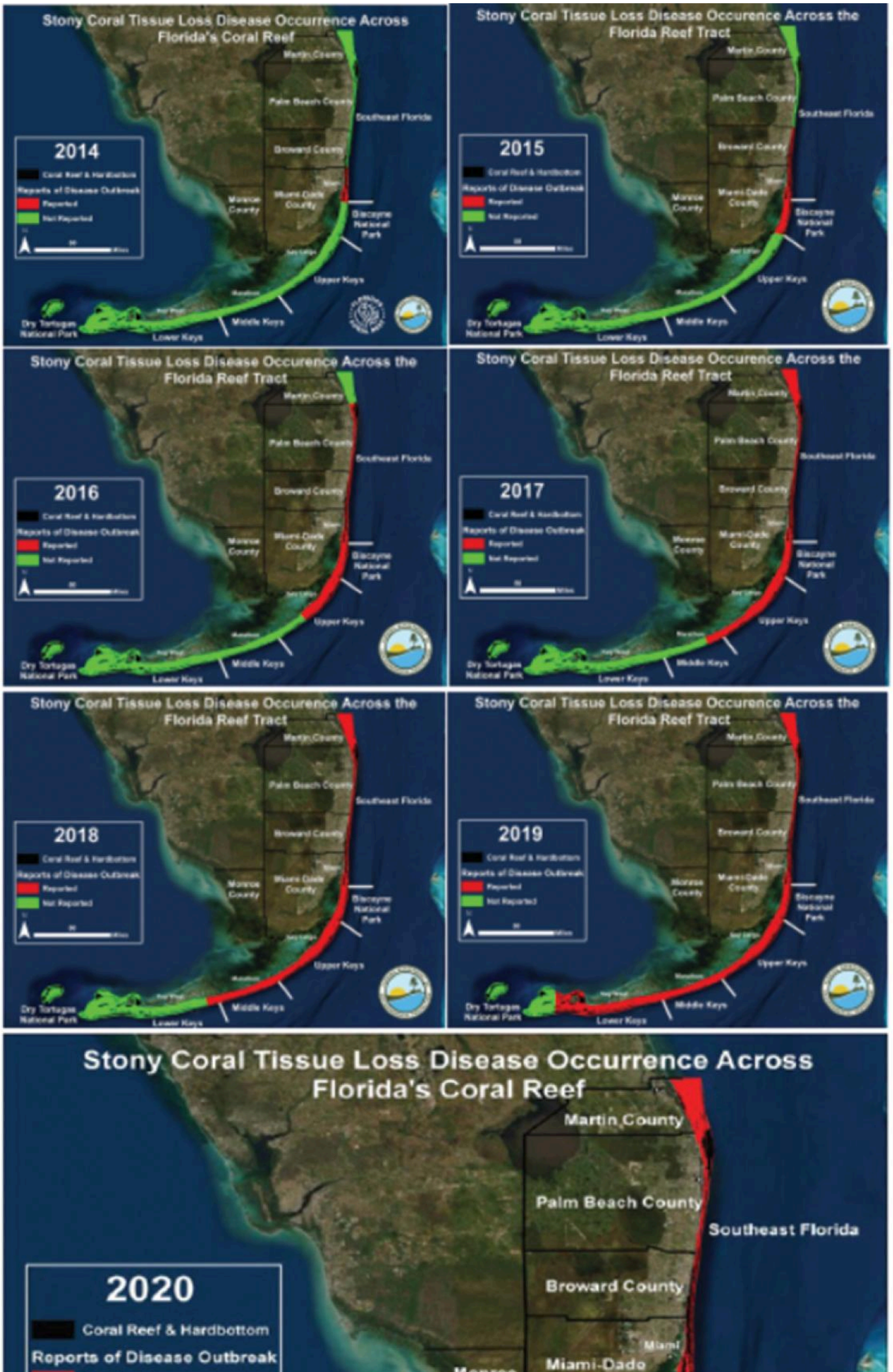
multi-faceted strategy to effectively address the various challenges facing these ecosystems. The increasing availability of open-source tools and platforms is playing a crucial role in enhancing the accessibility and efficiency of coral reef monitoring efforts worldwide. Platforms like MERMAID and analytical tools like CoralSoundExplorer lower the barriers to data management, analysis, and visualization, potentially fostering greater collaboration among researchers and conservationists and leading to more informed and impactful conservation actions.

2.1. The Ecological Significance of CREMP's Core Data Points

The Coral Reef Evaluation and Monitoring Project (CREMP) meticulously collects a range of data points, each providing critical insights into the ecological health and functioning of Florida's coral reefs. Among these, stony coral percent cover stands as a primary indicator of reef health. This metric represents the proportion of the reef area that is covered by living stony corals.[48] A high percentage of stony coral cover generally signifies a thriving reef ecosystem, providing essential habitat structure and food resources for a multitude of marine species.[2] Conversely, a decline in stony coral cover often indicates reef degradation resulting from various stressors such as coral bleaching, disease outbreaks, and storm damage.[48] CREMP's long-term data has documented a significant decrease in stony coral cover in the Florida Keys between 1996 and 2015, highlighting the impact of these stressors.[48] The loss of coral cover can have cascading effects, negatively impacting fish communities and reducing the overall biodiversity of the reef.[52] Reefs with higher stony coral cover are generally considered to be in a healthier state, underscoring the importance of this metric in assessing reef condition.[53]

Stony coral species richness, another core data point, refers to the number of different stony coral species present within a given area.[13] This metric is a fundamental measure of biodiversity, which is crucial for maintaining the stability and resilience of the reef ecosystem in the face of environmental changes.[49] A greater diversity of coral species can enhance the overall productivity of the reef.[56] CREMP data revealed a Sanctuary-wide decline in stony coral species richness in the Florida Keys between 1996 and 2004, indicating a potential loss of biodiversity.[27] Coral communities with high species richness may also exhibit greater capacity to withstand and recover from climatic disturbances.[54] The species composition and richness of local coral assemblages are influenced by a complex interplay of local factors and broader regional ecological processes, making long-term monitoring of this metric essential.[57]

Octocoral density, the number of octocoral colonies per unit area, is also a significant indicator tracked by CREMP.[60] Octocorals, including sea fans and sea rods, are often abundant components of reef communities and contribute to the structural complexity of the habitat.[60] In some reef habitats, octocorals can be as numerous as or even outnumber stony corals.[14] Notably, in certain Caribbean reefs experiencing declines in stony corals, octocoral forests have become the dominant benthic community.[61] Octocorals are often considered to be more resilient to certain disturbances compared to stony corals, potentially due to their faster growth and reproduction rates.[14] CREMP's long-term findings have shown a significant trend of octocorals replacing elkhorn and staghorn corals on shallow forereefs in Florida, highlighting a potential shift in community composition.[14]



Stony Coral Tissue Loss Disease Occurrence Across Florida's Coral Reef
2014
Stony Coral Tissue Loss Disease Occurence Across the Florida Reef Tract
2015
Stony Coral Tissue Loss Disease Occurence Across the Florida Reef Tract
2016
Stony Coral Tissue Loss Disease Occurence Across the Florida Reef Tract
2017
Stony Coral Tissue Loss Disease Occurence Across the Florida Reef Tract
2018
Stony Coral Tissue Loss Disease Occurence Across the Florida Reef Tract
2019
Stony Coral Tissue Loss Disease Occurrence Across Florida's Coral Reef
Martin County
Palm Beach County
Southeast Florida
2020
Broward County
Coral Reef & Hardbottom
Reports of Disease Outbreak
Miami
Miami-Dade

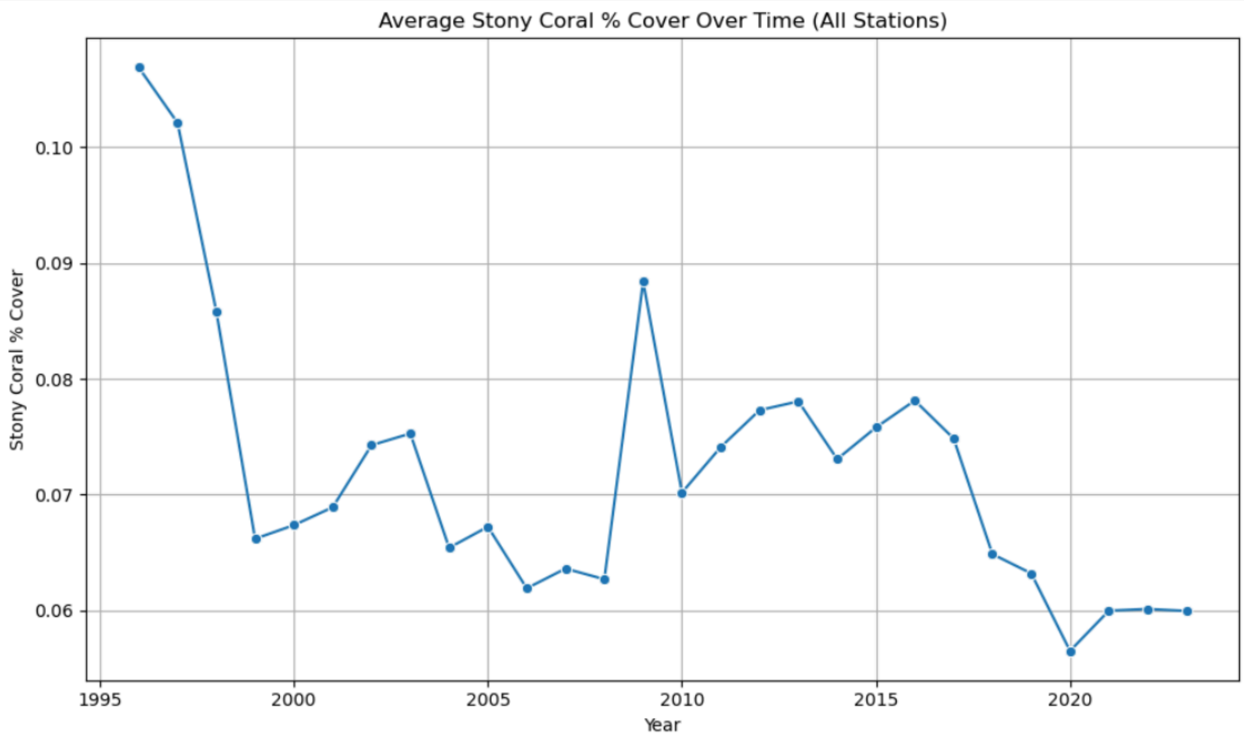
Live tissue area of stony corals, representing the surface area of a coral colony covered by living tissue, is a direct measure of coral health and the impact of stressors.[5] A healthy coral colony will have a large area of live tissue, while a reduction in this area often indicates stress, disease (such as SCTLD, Black Band Disease (BBD), or White Band Disease (WBD)), or bleaching.[6] Stony Coral Tissue Loss Disease (SCTLD), for instance, is characterized by rapid and extensive loss of live tissue in susceptible coral species.[8] Tracking changes in live tissue area over time is crucial for monitoring the progression of diseases and the recovery of affected corals.[68]

Finally, CREMP monitors specific coral health conditions, including Bleaching (BLH), Black Band Disease (BBD), and White Band Disease (WBD), which provide valuable insights into the types of stressors affecting the reefs. Bleaching, identified by pale or white coral tissue, is a common stress response to elevated water temperatures and other environmental factors.[5] While bleached corals can recover if conditions improve, prolonged or severe bleaching can lead to starvation and increased susceptibility to disease.[5] Florida's coral reefs experienced widespread bleaching during the summer of 2023, underscoring the severity of thermal stress events.[1] Black Band Disease (BBD) is an infectious coral disease characterized by a dark band of microorganisms that migrates across the coral colony, causing tissue loss and ultimately death.[71] BBD is associated with a complex microbial community and tends to be more prevalent during warmer months.[71] White Band Disease (WBD) is another tissue loss disease that affects certain species of Caribbean corals, resulting in rapid denudation of the coral skeleton.[72] The occurrence and prevalence of these coral diseases can significantly impact coral cover and the overall structure of reef communities.[4] The various data points collected by CREMP are intricately connected. For instance, elevated water temperatures can trigger coral bleaching, which in turn weakens the coral's defenses, making it more vulnerable to infectious diseases like BBD and WBD. The progression of these diseases leads to a reduction in the live tissue area of the coral, and if the stress is severe or prolonged, it can ultimately result in coral mortality, impacting both coral cover and species richness on the reef. The observed shift in dominance from stony corals to octocorals in some areas monitored by CREMP suggests a potential long-term ecological transformation in response to changing environmental conditions. As stony corals, which are more susceptible to stressors like ocean acidification due to their calcium carbonate skeletons, decline, octocorals, with their different skeletal composition and potentially greater tolerance, may become increasingly prevalent. Therefore, the continuous monitoring of octocoral density and health by CREMP is becoming increasingly crucial for understanding the future trajectory of Caribbean reef ecosystems.

3. Comprehensive Data and Exploration

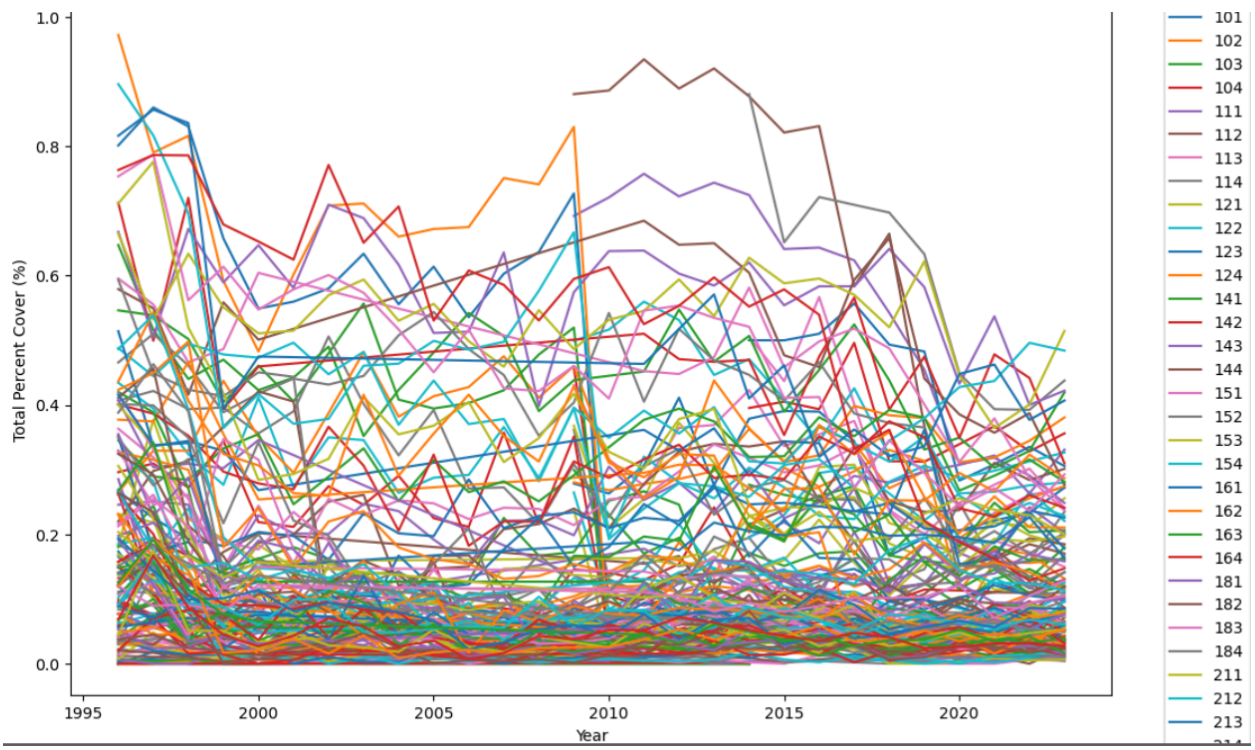
From the Florida Keys Coral Reef Evaluation Monitoring Project data was extracted and total of 12 csv files were used and processed for valuable findings. The operations and finding done are

3.1. Average Stony Coral % Cover Over Time (All Stations)



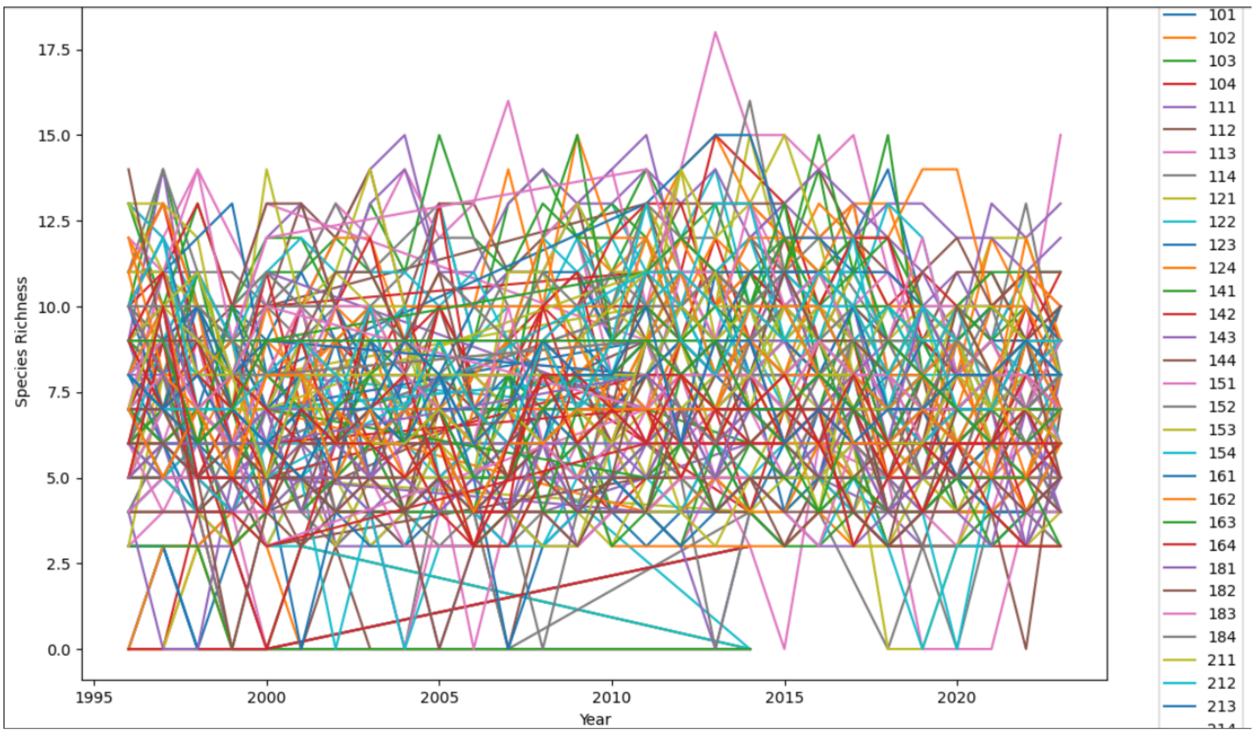
The analysis of average stony coral percent cover across all stations from 1996 to 2023 reveals a concerning decline in reef health, with significant implications for ecosystem stability. Data from stations 101 to 814 show the highest average cover at 0.11% in 1996, dropping to a low of 0.06% in 2020, and partially recovering to 0.08% by 2022. The cover was calculated by summing individual species' contributions across stations, providing a comprehensive metric of reef vitality. This decline reflects the cumulative impact of environmental stressors, including rising sea temperatures, coral bleaching events, disease outbreaks, and anthropogenic pressures like coastal development. The sharp drop around 2020 may correlate with global bleaching events or localized disturbances, such as hurricanes or disease spikes. The partial recovery by 2022 suggests some resilience, possibly due to natural recovery or management interventions. However, the overall downward trend underscores the vulnerability of stony corals, which are critical for reef structure and biodiversity. Reduced cover can lead to diminished habitat for marine species, weakened coastal protection, and economic losses in tourism and fisheries. The findings emphasize the urgent need for enhanced conservation measures, such as reducing nutrient pollution, protecting water quality, and mitigating climate change impacts. Targeted restoration, like coral gardening, could bolster cover at degraded sites. Continuous monitoring is essential to track recovery and adapt strategies, ensuring the long-term sustainability of Florida's reefs.

3.2. Stony Coral Percent Over Time



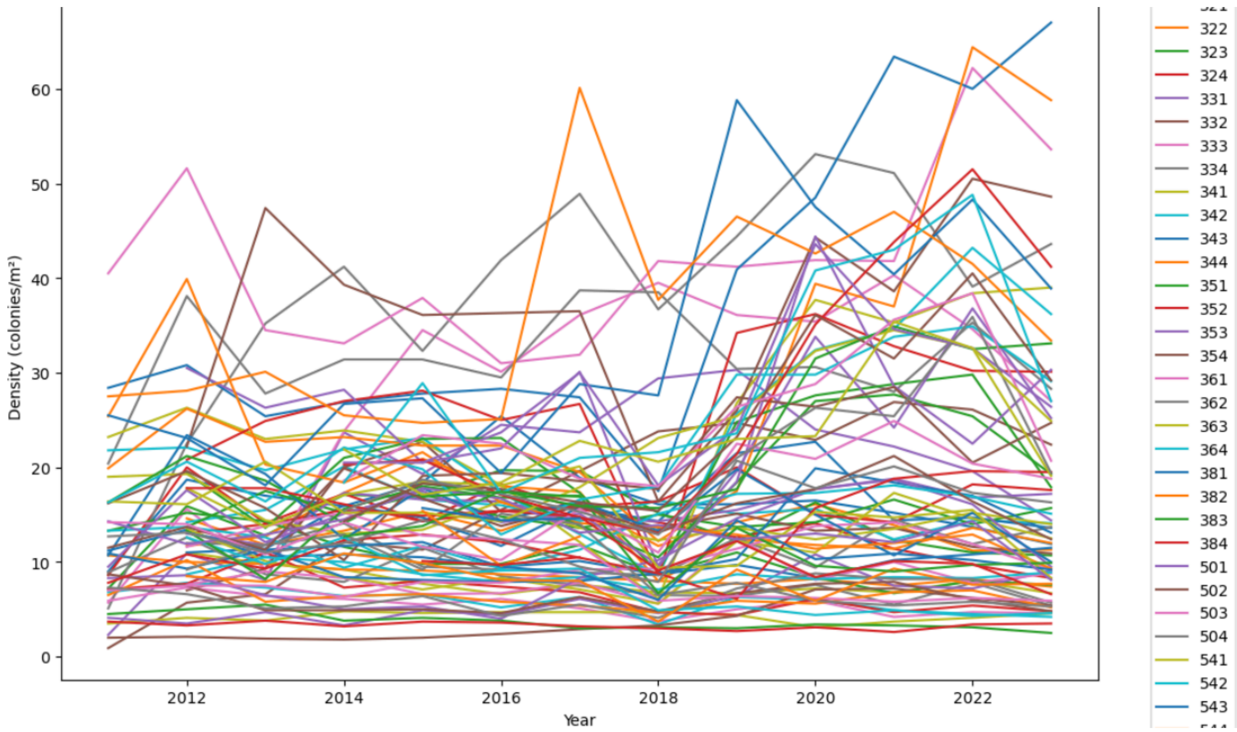
This analysis visualizes stony coral percent cover for individual stations (101 to 814) from 1996 to 2023 using line plots, highlighting spatial and temporal variability in reef health. Each line represents a station's cover trajectory, calculated by summing species-specific cover annually. The plots reveal diverse patterns: some stations maintain relatively stable cover, while others exhibit sharp declines, particularly around 2020, aligning with the sanctuary-wide low of 0.06%. Post-2020, certain stations show recovery, but many remain below 1996 levels. This variability suggests localized environmental conditions, such as water quality, temperature, or disease prevalence, significantly influence outcomes. For instance, stations near urban areas may face higher nutrient loads, exacerbating coral stress, while those in protected zones may fare better. The data underscore the complexity of reef dynamics, where global stressors like warming oceans interact with site-specific factors. The findings advocate for tailored management approaches, such as enhancing water quality at vulnerable sites or prioritizing protection for resilient stations. The decline in cover threatens ecosystem services, including habitat provision and coastal defense, necessitating urgent action. Restoration efforts, like outplanting corals, could target stations with steep declines, while marine protected areas may safeguard stable sites. The analysis highlights CREMP's value in providing granular data, enabling precise interventions to mitigate further losses and promote reef recovery.

3.3. Stony Coral Species Richness Over Time



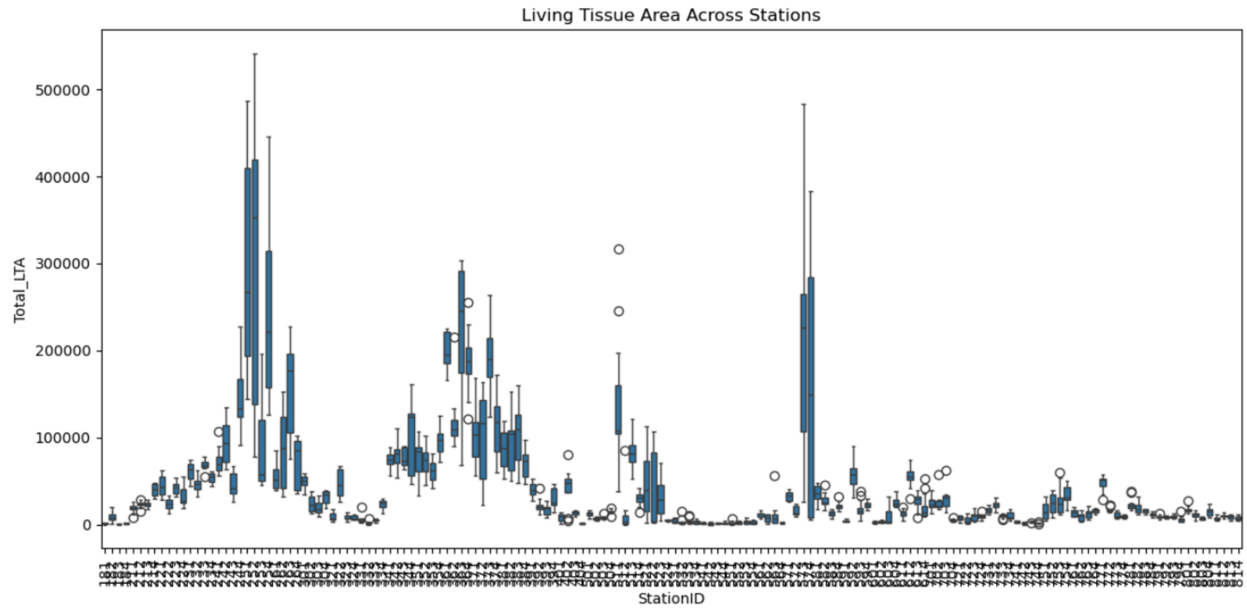
The examination of stony coral species richness over time tracks the number of species at stations 101 to 814 from 1996 to 2023, using line plots to visualize changes. Species richness, determined by counting unique species per site annually, varies across stations, with some maintaining stable diversity and others showing declines, particularly post-2010. The data reveal no consistent sanctuary-wide trend, indicating localized influences like habitat degradation, disease, or water quality. A strong positive correlation with total percent cover (1.00, from the correlation heatmap) suggests that higher cover supports greater biodiversity. Stations with declining richness often coincide with reduced cover, reflecting stressors that impact both abundance and diversity. This relationship is critical, as species richness enhances ecosystem resilience by providing functional redundancy. The findings highlight the need to prioritize coral cover preservation to maintain biodiversity, as losses could destabilize reef ecosystems. Management should focus on mitigating stressors like pollution and temperature spikes, which disproportionately affect vulnerable sites. Restoration efforts, such as reintroducing diverse coral species, could enhance richness at degraded stations. The analysis underscores CREMP's role in capturing long-term trends, informing strategies to protect biodiversity and ensure the ecological integrity of Florida's reefs.

3.4. Octocoral Density Over Time



Octocoral density, measured in colonies per square meter, was analyzed for stations 321 to 814, plus 261 to 264, from 2011 to 2023, using line plots to depict temporal trends. The data show significant variability, with some stations maintaining stable density, others peaking around 2017, and some declining sharply by 2018. This variability suggests octocorals respond differently to environmental changes, such as temperature shifts, nutrient availability, or predation. Unlike stony corals, octocorals exhibit greater resilience at certain sites, maintaining higher densities despite stressors. This resilience makes them valuable for restoration, as they contribute to reef structure and habitat complexity. The lack of a uniform trend across stations indicates localized factors, such as water flow or substrate type, play a significant role. The findings suggest that protecting high-density octocoral sites could enhance overall reef health, while understanding drivers of decline at other sites is critical. Management strategies should include reducing nutrient pollution and monitoring temperature impacts, as these may influence octocoral populations. The analysis highlights the importance of integrating octocoral data into conservation plans, leveraging their ecological role to support reef recovery and resilience in the face of ongoing environmental challenges.

3.5. Living Tissue Area Across Stations



The living tissue area (LTA) analysis quantifies total living coral tissue across stations 181 to 814 by summing LTA across species, revealing spatial variability in reef vitality.

Stations with higher LTA indicate healthier coral communities, while those with lower LTA suggest stress or degradation. The data highlight heterogeneity in reef health, with some sites thriving and others struggling, likely due to differences in water quality, sedimentation, or temperature stress. For instance, stations in areas with strong currents may benefit from better nutrient exchange, supporting higher LTA, while those near coastal runoff may face sediment smothering.

LTA serves as a complementary metric to percent cover, providing a direct measure of living coral biomass. The findings advocate for protecting high-LTA stations as ecological strongholds, while low-LTA sites require targeted interventions, such as improving water quality or reducing physical damage. This spatial variability underscores the need for site-specific management within the CREMP framework.

By prioritizing areas with robust LTA, conservation efforts can maximize ecological benefits, while addressing stressors at degraded sites could reverse declines. The analysis reinforces the importance of comprehensive monitoring to guide resource allocation and enhance reef health across Florida's diverse coral ecosystems.

3.6. Spatial Patterns Sample

```
Spatial Patterns Sample:
Year       1996  1997  1998  1999  2000  2001  2002  2003  2004  2005  ...  \
StationID                                                              ...
101           1     1     1     1     1     0     0     0     0     0  ...
102           1     1     1     1     1     1     0     0     0     0  ...
103           1     1     1     1     1     1     0     0     0     0  ...
104           1     1     1     1     1     0     0     0     0     0  ...
111           1     1     1     1     1     0     0     0     0     0  ...

Year       2014  2015  2016  2017  2018  2019  2020  2021  2022  2023
StationID
101           1     0     0     0     0     0     0     0     0     0
102           1     0     0     0     0     0     0     0     0     0
103           1     0     0     0     0     0     0     0     0     0
104           1     0     0     0     0     0     0     0     0     0
111           1     0     0     0     0     0     0     0     0     0

[5 rows x 28 columns]
```

The spatial patterns sample examines monitoring effort across stations 101 to 111 from 1996 to 2023, using a binary matrix (1 for monitored, 0 for not monitored) to track activity.

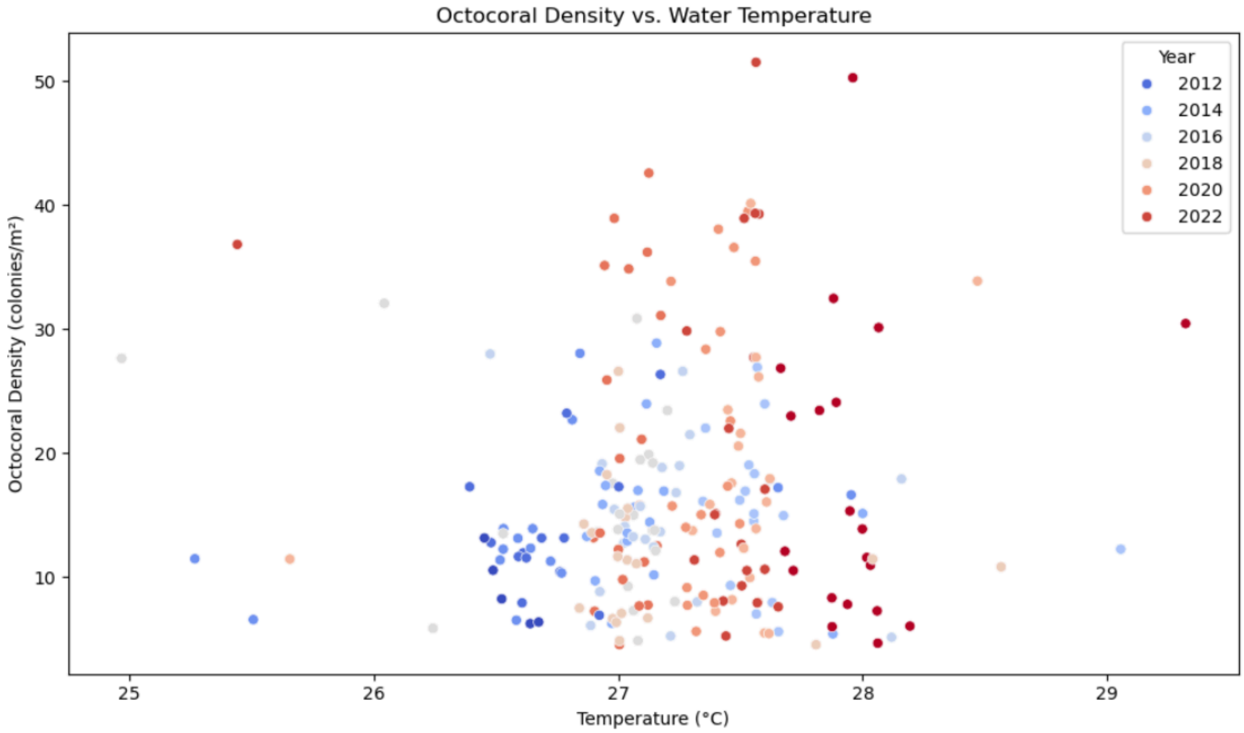
The data show consistent monitoring from 1996 to 2000, reduced activity from 2001 to 2013, and a resurgence at some stations by 2014. This pattern reflects changes in CREMP's protocols, possibly due to funding or logistical constraints.

The cessation of monitoring at certain stations post-2014 creates data gaps, potentially skewing long-term trend analyses. These gaps could obscure critical events, such as bleaching or disease outbreaks, affecting the accuracy of ecological assessments.

The findings highlight the importance of sustained monitoring to capture comprehensive trends, as intermittent data collection limits the ability to detect subtle changes. Management should prioritize consistent coverage across all stations, ensuring robust datasets for future analyses.

The analysis also underscores CREMP's adaptability, as shifts in monitoring reflect efforts to align with management priorities. By addressing these gaps, CREMP can enhance its ability to inform conservation strategies, supporting the long-term health of Florida's reefs through data-driven decision-making.

3.7. Octocoral Density vs. Water Temperature



A scatter plot explores the relationship between water temperature (25°C to 29.5°C) and octocoral density (0 to 52 colonies/m²) from 2012 to 2022, with points color-coded by year. Most data cluster between 26.5°C and 28°C, showing wide density variation within this range, from below 10 to over 30 colonies/m².

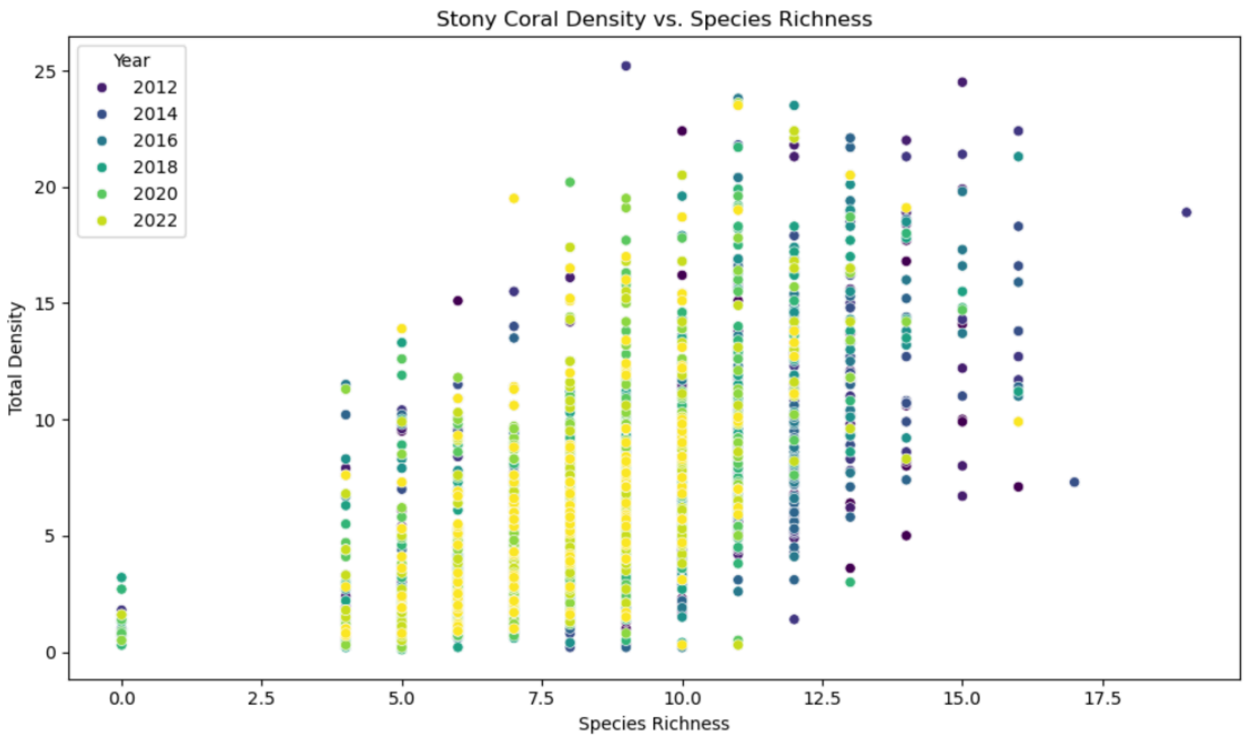
No strong linear correlation is evident, and the intermixing of years suggests no clear temporal trend.

This indicates that temperature alone does not drive octocoral density, with other factors like nutrient levels, water flow, or predation likely playing significant roles. The concentration of data within a narrow temperature range reflects typical conditions in the Florida Keys, but the variability in density underscores the complexity of octocoral ecology.

The findings suggest that management should focus on a holistic approach, addressing multiple environmental factors to support octocoral populations. Protecting sites with high density could enhance reef resilience, while studying low-density sites may reveal specific stressors.

The analysis highlights the need for integrated monitoring to understand octocoral dynamics fully, ensuring their ecological contributions are leveraged in conservation efforts.

3.8. Stony Coral Density vs. Species Richness



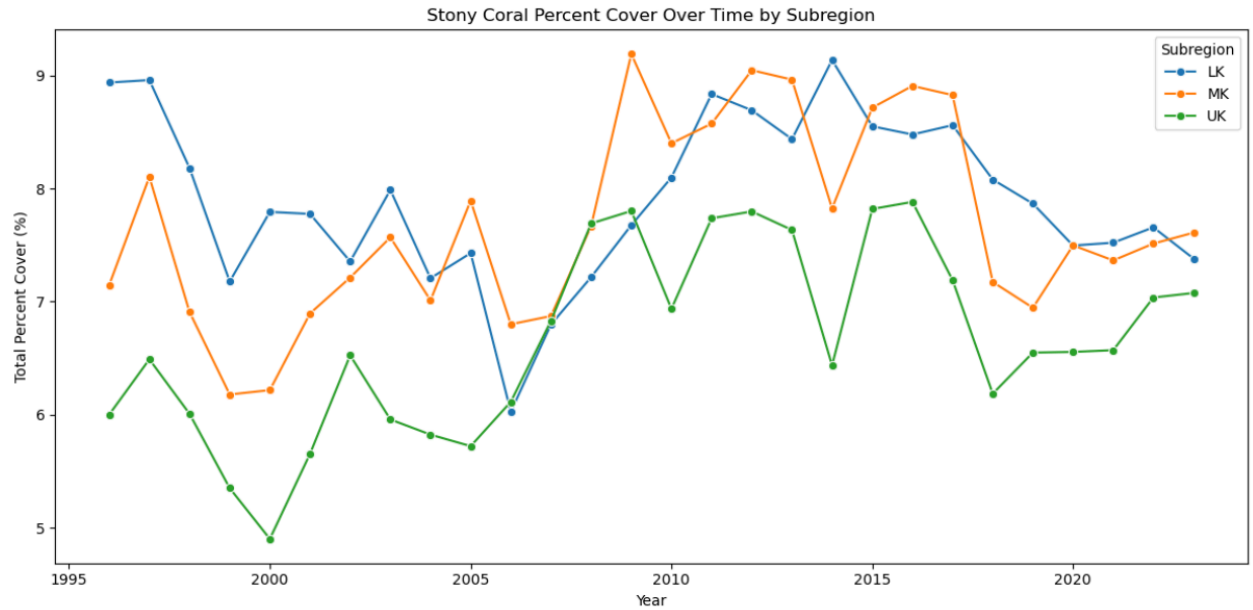
This scatter plot examines stony coral species richness (0 to 18 species) versus total density (0 to 76) from 2012 to 2022, with points color-coded by year. The data show a weak correlation, with a wide range of density values for any given richness level, indicating that richness is not a strong predictor of density. The absence of year-specific clustering suggests consistent variability over time, with no clear temporal shift in the relationship.

This weak correlation implies that other factors, such as environmental stressors, competition, or habitat conditions, significantly influence density. For example, high-density sites may reflect favorable conditions like clear water, while low-density sites could indicate stress from sedimentation or disease.

The findings highlight the complexity of coral community dynamics, where density and richness respond to different drivers. Management should monitor both metrics to capture a complete picture of reef health, as focusing solely on richness could overlook density declines.

The analysis underscores CREMP's value in providing multidimensional data, enabling nuanced conservation strategies to address specific ecological challenges and support robust reef ecosystems.

3.9. Average Coral Density Over Time by Subregion



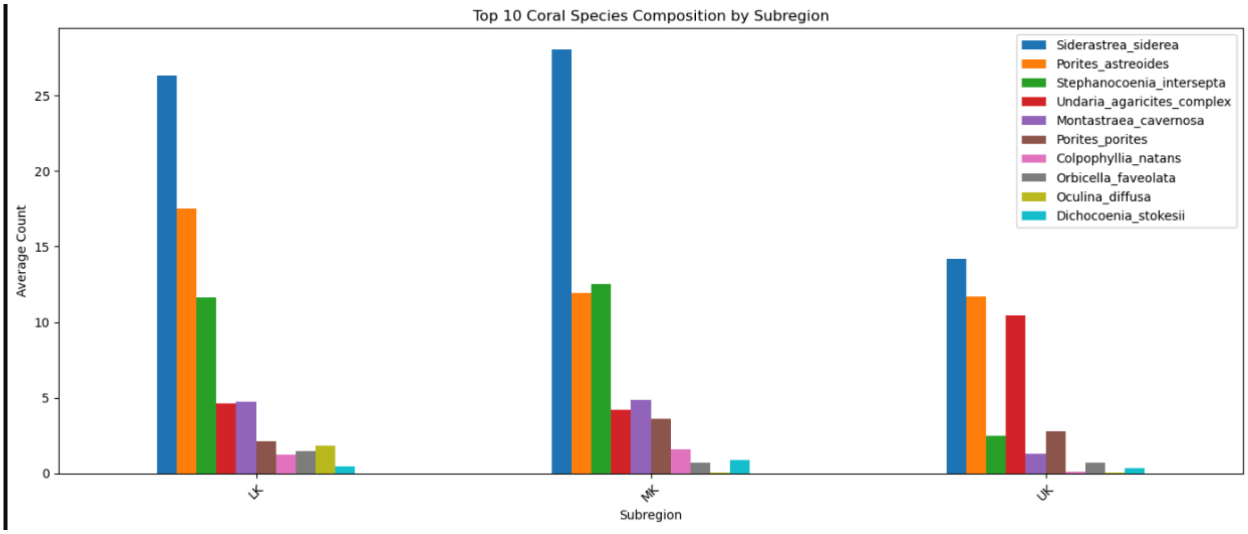
The line plot of average coral density across subregions (LK, MK, UK) from 2011 to 2023 reveals distinct trends, reflecting subregional environmental differences.

LK shows relative stability, peaking at 42 in 2017 and ending at 37 in 2023. MK exhibits significant fluctuations, peaking at 42.5 in 2017, dropping to 30.5 in 2018, and rising to 40 by 2023. UK displays a gradual increase from 20 in 2018 to 29.5 in 2023.

These patterns suggest MK faces volatile conditions, possibly due to temperature spikes or nutrient surges, while UK's recovery indicates improving conditions. LK's stability may reflect consistent management or favorable habitats. The data highlight the need for subregion-specific strategies: stabilizing MK's conditions, supporting UK's recovery, and maintaining LK's health. Reduced density in any subregion can weaken reef ecosystems, impacting biodiversity and coastal protection.

The findings advocate for targeted interventions, such as reducing runoff in MK or enhancing protected areas in UK, to bolster density and ensure long-term reef resilience across Florida's diverse subregions.

3.10. Top 10 Coral Species Composition by Subregion



A bar plot illustrates the average counts of the top 10 coral species across LK, MK, and UK, revealing subregional differences in community structure. Siderastrea siderea dominates, with MK showing the highest count (28), followed by Porites astreoides across all subregions. Stephanocoenia intersepta is abundant in LK (11.5) and MK (12.5) but scarce in UK (2.5), while Undaria agaricites complex is notably higher in UK (10.5). These patterns reflect variations in habitat suitability, water quality, or stressors like temperature.

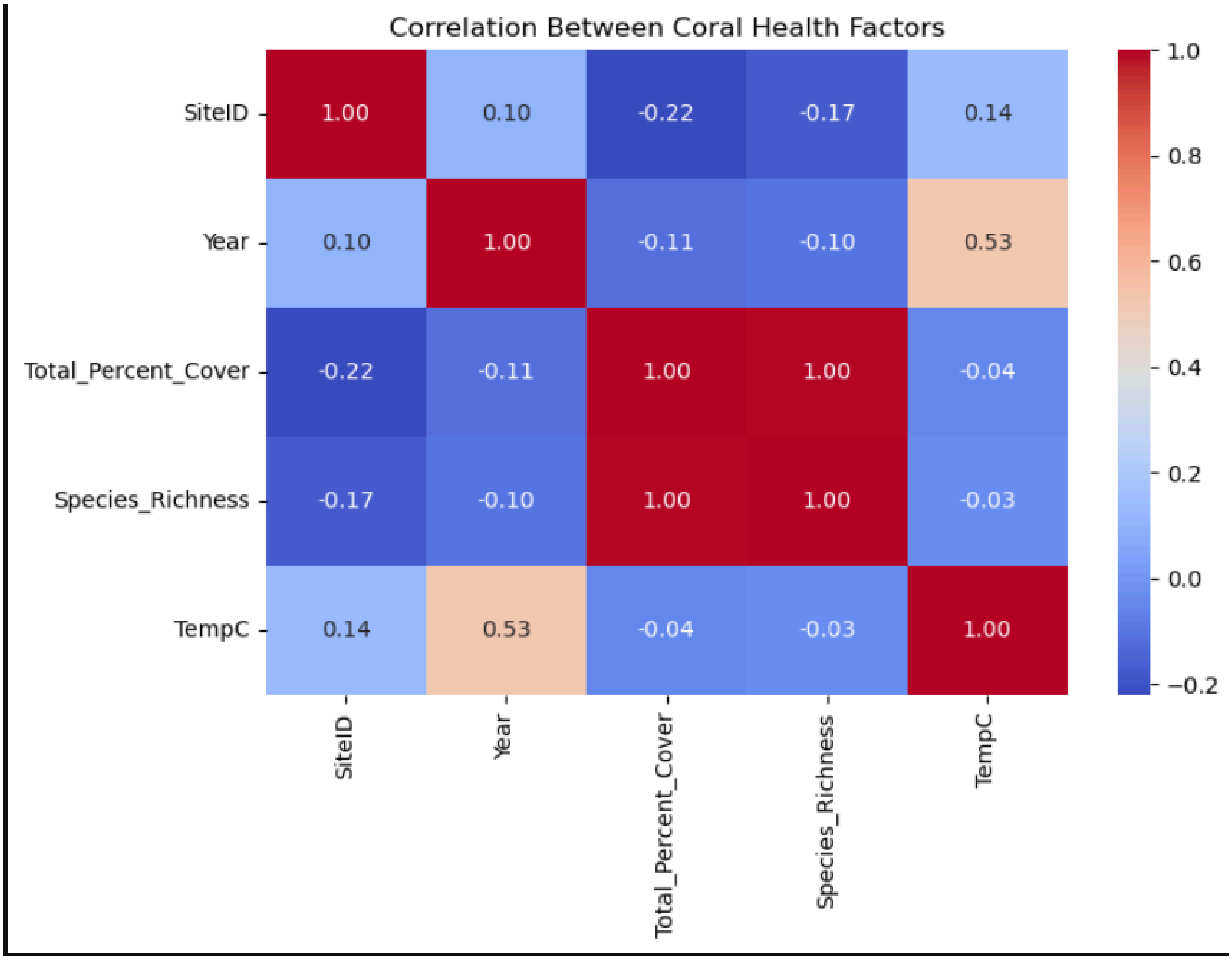
Dominant species like Siderastrea siderea are critical for reef stability, and their prevalence suggests resilience in certain subregions.

However, the lower abundance of some species in UK indicates potential vulnerabilities. The findings highlight the need to protect dominant species while addressing factors limiting others, such as pollution or sedimentation in UK.

Management should leverage these insights to prioritize species-specific conservation, ensuring diverse and robust coral communities.

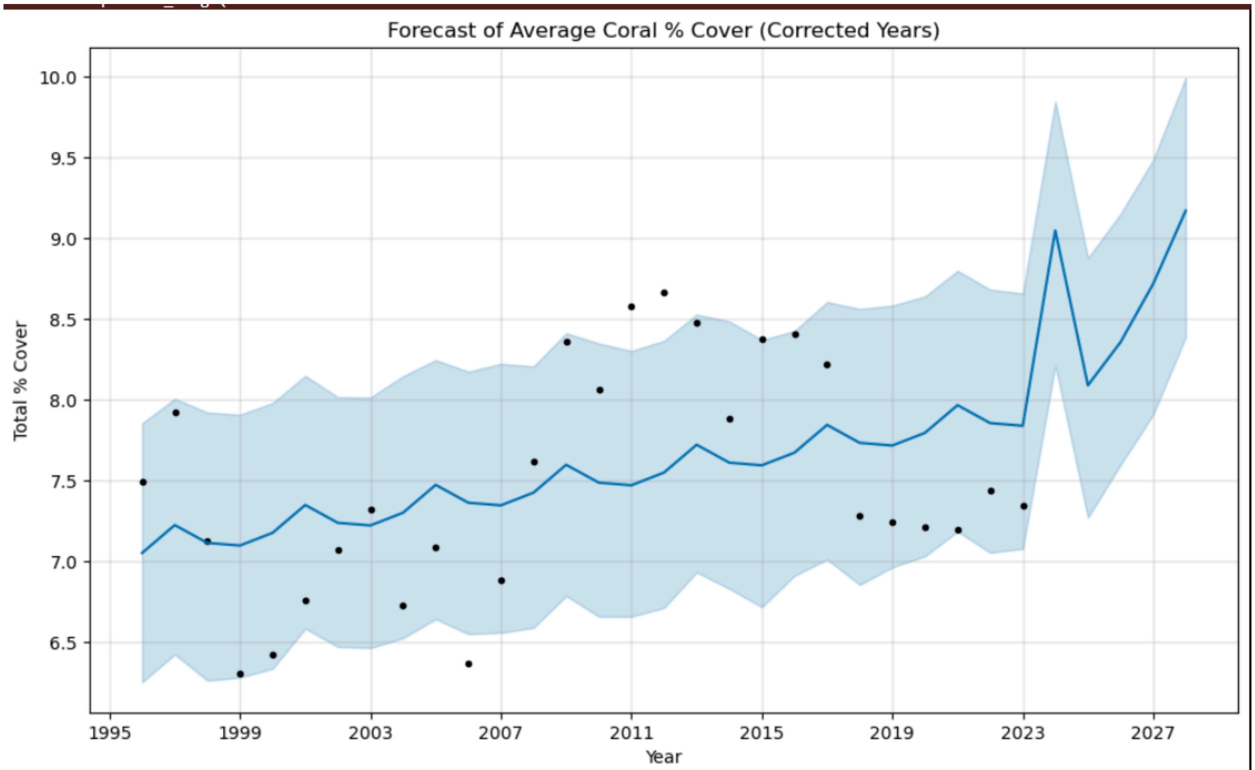
The analysis underscores CREMP’s role in identifying subregional ecological patterns, guiding targeted interventions to enhance reef health and biodiversity.

3.11. Correlation Between Coral and Health Factors



A heatmap analyzes pairwise correlations between SiteID, Year, Total_Percent_Cover, Species_Richness, and TempC, providing insights into reef health drivers. The strongest correlation (1.00) is between Total_Percent_Cover and Species_Richness, indicating that higher cover supports greater biodiversity, a critical factor for ecosystem resilience. TempC shows a moderate positive correlation with Year (0.53), reflecting rising temperatures over time, but weak negative correlations with cover (-0.04) and richness (-0.03), suggesting minimal direct impact. SiteID correlations are weak, indicating no strong spatial bias. The cover-richness link underscores the importance of maintaining coral cover to preserve biodiversity, as declines could trigger cascading ecological losses. Rising temperatures, while not strongly correlated with cover, pose a long-term threat through bleaching risks. The findings advocate for strategies to enhance cover, such as reducing nutrient pollution, while monitoring temperature trends to mitigate climate impacts. The analysis highlights CREMP's ability to quantify ecological relationships, informing management to prioritize cover preservation and address emerging stressors like warming oceans.

3.12. Forecast of Average Coral % Cover

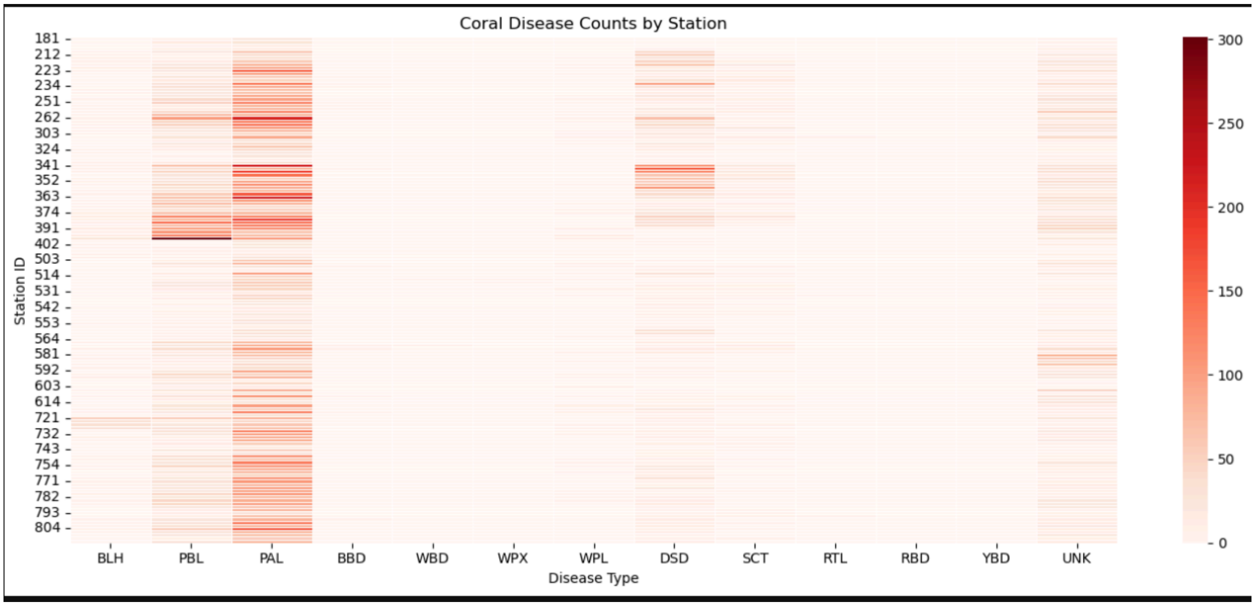


A line plot forecasts average coral percent cover from 1996 to 2028 using historical data (black dots) and a Prophet model (blue line with confidence interval). Historical data show a decline from 0.11% in 1996 to 0.06% in 2020, with a slight recovery to 0.08% by 2022. The forecast suggests a gradual upward trend post-2023, but the widening confidence interval indicates increasing uncertainty. The model captures long-term trends and variability, reflecting influences like bleaching events, disease, or management interventions.

The projected increase offers hope for recovery, possibly driven by conservation efforts or natural resilience, but uncertainty underscores the need for proactive measures. Declining cover threatens reef ecosystems, reducing habitat and coastal protection.

The findings advocate for intensified restoration, such as coral outplanting, and mitigation of stressors like temperature and pollution to support the forecasted recovery. Continuous monitoring is essential to validate the forecast and adapt strategies, ensuring Florida's reefs regain ecological integrity and resilience in the face of ongoing environmental challenges.

3.13. Coral Disease Count by Station



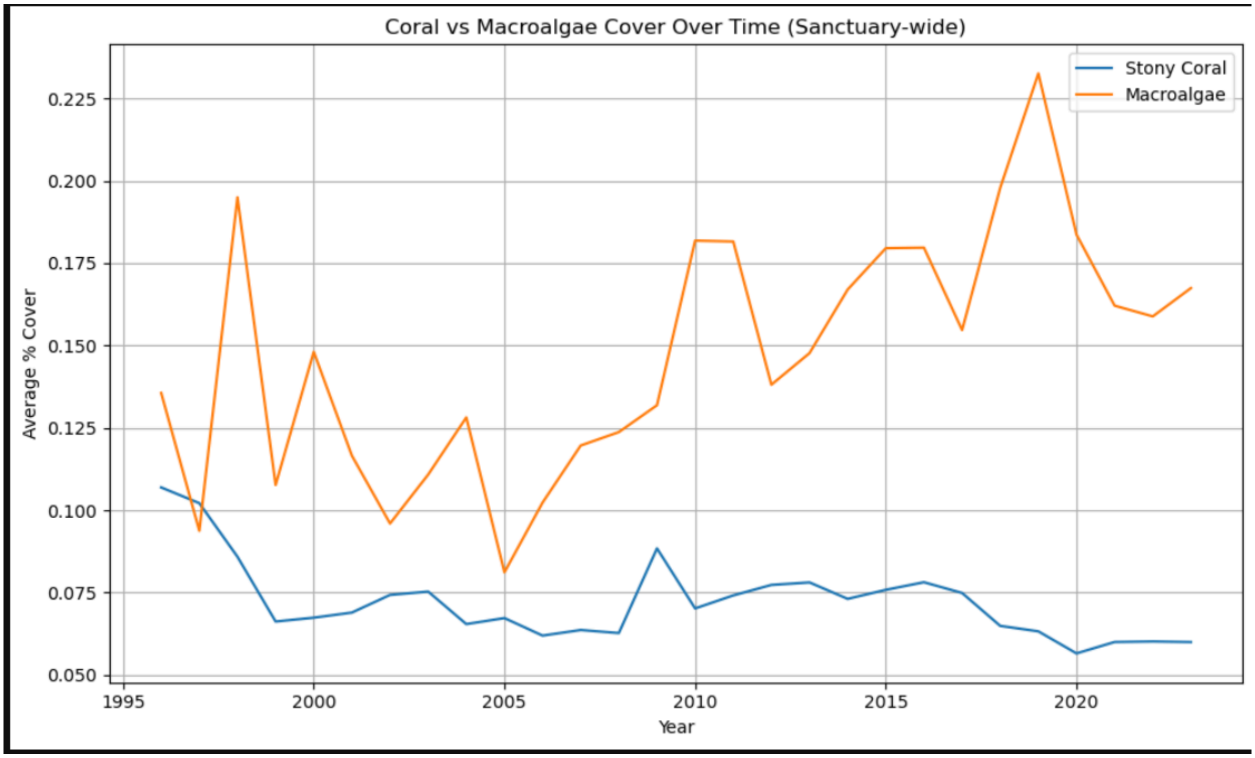
A heatmap visualizes coral disease counts by station (e.g., 352, 363, 374, 402) and disease type (e.g., PBL, PAL, UNK), with color intensity indicating prevalence. PBL, PAL, and UNK are the most prevalent, with stations 352, 363, and 374 showing high counts across multiple diseases, and 402 notably high for PBL. Other diseases, like BBD and WBD, have lower counts.

This distribution suggests widespread disease pressure, with specific stations facing intense impacts, possibly due to local conditions like poor water quality or high temperatures. High disease prevalence threatens coral survival, reducing cover and biodiversity.

The findings highlight the need for targeted disease management, such as improving water quality at high-risk stations or developing disease-resistant coral strains. The analysis underscores CREMP's role in identifying disease hotspots, enabling prioritized interventions to mitigate impacts and protect vulnerable reefs.

Ongoing monitoring is critical to track disease trends and assess management effectiveness, ensuring the long-term health of Florida's coral ecosystems.

3.14. Coral vs. Macroalgae Cover Over Time (Sanctuary-Wide)

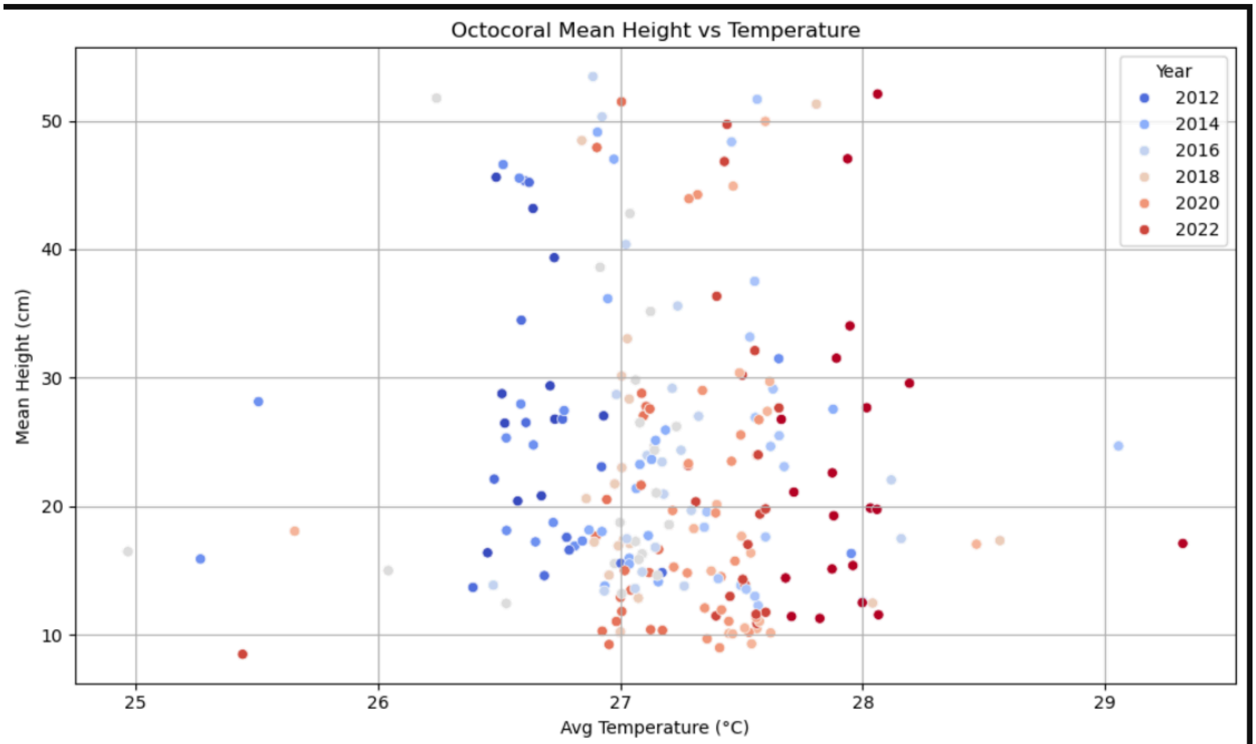


A line plot compares stony coral and macroalgae percent cover from 1996 to 2022, revealing competitive dynamics. Coral cover starts at 0.11% in 1996, drops to 0.07% by 1999, and fluctuates between 0.065% and 0.08% thereafter, dipping to 0.07% in 2020. Macroalgae cover begins at 0.135%, peaks at 0.195% in 1998, and shows significant variability, with a notable peak at 0.235% in 2019 and a decline to 0.17% by 2022. The upward trend in macroalgae post-2008 suggests it outcompetes corals under certain conditions, possibly due to nutrient enrichment.

This shift threatens reef health, as macroalgae can smother corals and reduce biodiversity. The findings advocate for nutrient management to curb macroalgae growth and support coral recovery.

Restoration efforts should focus on enhancing coral cover to restore ecological balance. The analysis highlights CREMP's ability to capture long-term trends, informing strategies to mitigate macroalgae dominance and promote reef resilience.

3.15. Octocoral Mean Height vs. Temperature



A scatter plot examines octocoral mean height (0 to 55 cm) versus average water temperature (25°C to 29.5°C) from 2012 to 2022, with points color-coded by year. Most data cluster between 26.5°C and 28°C, showing wide height variability, from below 10 cm to over 50 cm.

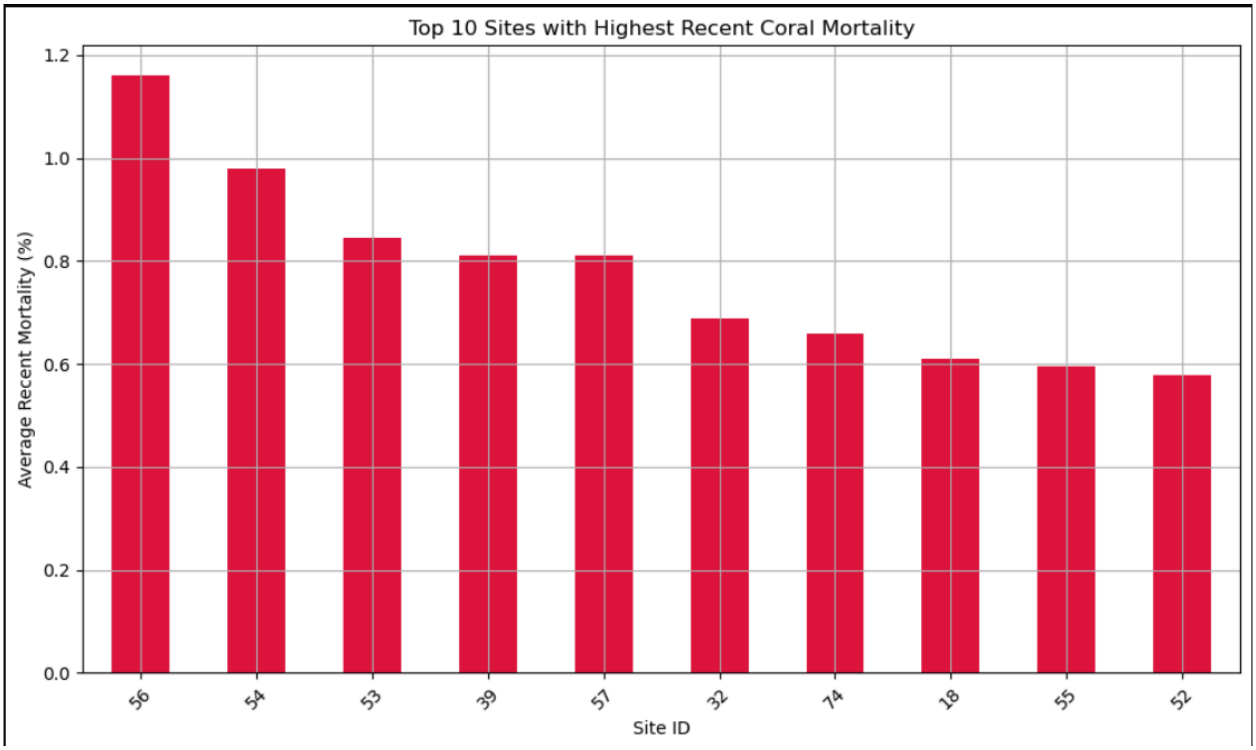
No strong correlation or temporal trend is evident, indicating temperature is not a primary driver of octocoral height. Other factors, such as water flow or nutrient availability, likely influence growth.

The concentration of data within a narrow temperature range reflects typical Florida Keys conditions, but the height variability underscores ecological complexity. The findings suggest that management should address multiple factors to support octocoral growth, which contributes to reef structure.

Protecting high-height sites could enhance resilience, while studying low-height sites may reveal stressors.

The analysis emphasizes the need for comprehensive monitoring to understand octocoral dynamics, ensuring their ecological role is maximized in conservation efforts.

3.16. Top 10 Sites with Highest Recent Coral Mortality



A bar plot identifies the top 10 sites with the highest recent coral mortality percentages, ranging from 0.6% to over 1.15%. Site 56 exhibits the highest mortality (>1.15%), followed by Site 54 (<1.0%) and Site 53 (0.85%).

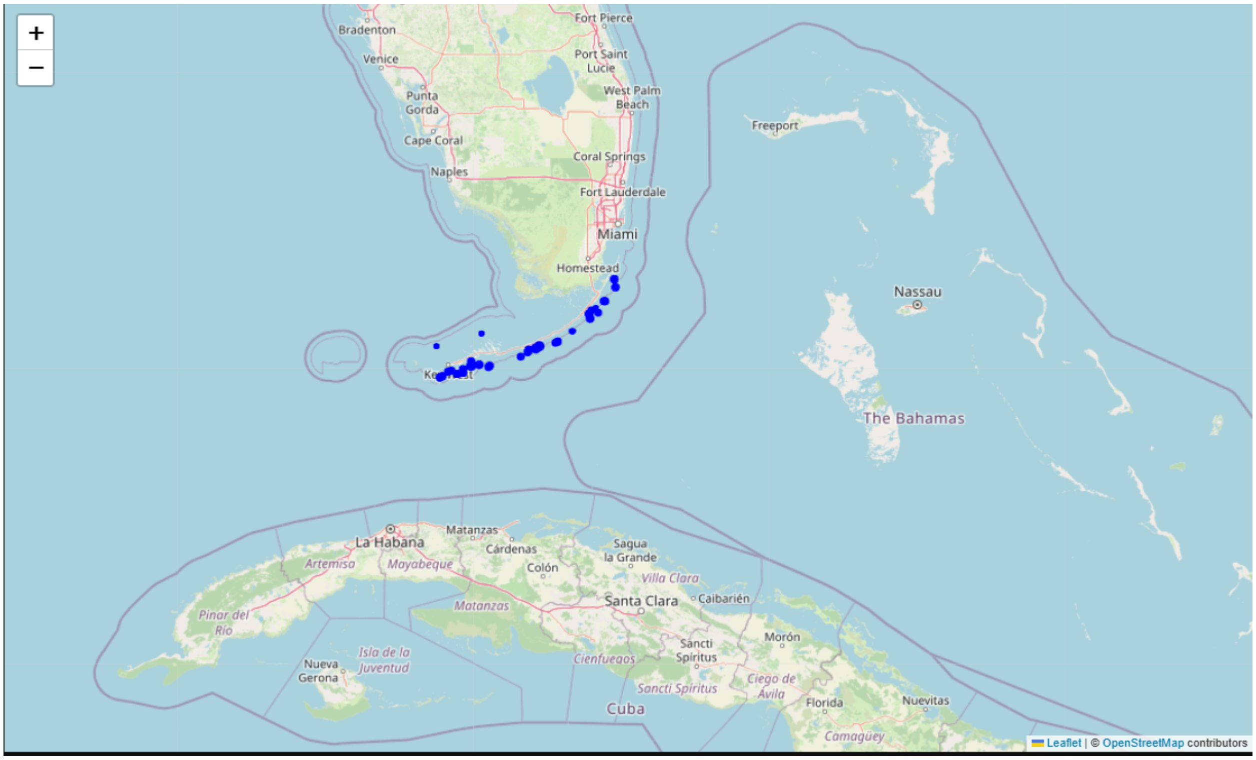
Sites 39, 57, 32, 74, 18, 55, and 52 range from 0.6% to 0.8%. High mortality indicates severe stress, possibly from disease, bleaching, or physical damage.

The concentration of high mortality at specific sites suggests localized stressors, such as poor water quality or temperature extremes.

The findings highlight the urgency of investigating these sites to identify and mitigate causes, such as improving water quality or reducing coastal impacts. Management should prioritize restoration at high-mortality sites, using techniques like coral transplantation, while protecting low-mortality sites to maintain resilience.

The analysis underscores CREMP's role in pinpointing vulnerable areas, guiding targeted interventions to reduce mortality and support reef recovery across Florida's coral ecosystems.

3.17. Stony Coral Cover by Station (Folium)



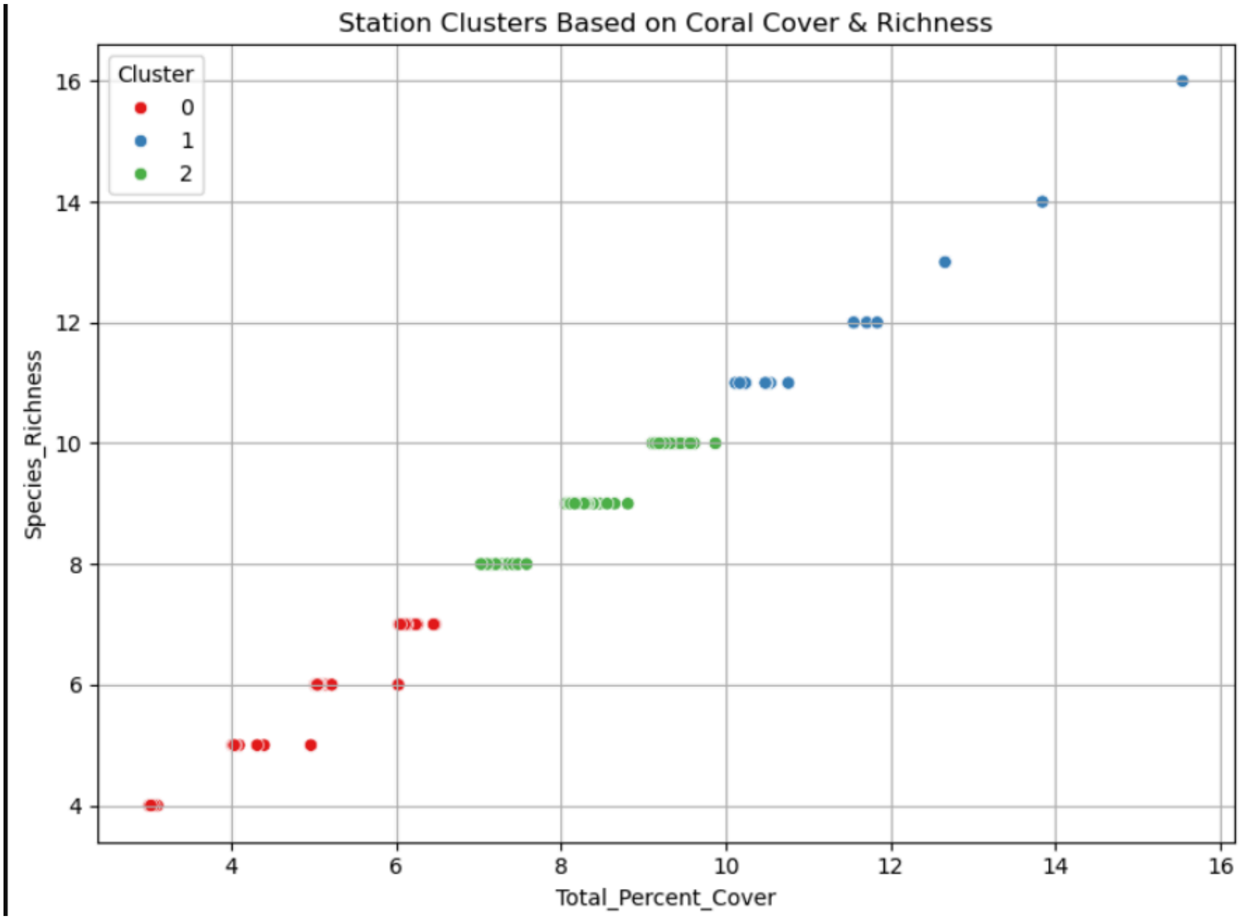
A folium map displays stony coral cover across stations in the Florida Keys, using blue circular markers whose size is proportional to cover. The map, centered on the Keys, shows stations concentrated along the island chain, with larger circles indicating higher cover and smaller ones lower cover.

This spatial distribution reveals heterogeneity, with some areas supporting robust coral communities and others showing degradation.

The pattern suggests environmental gradients, such as water quality or temperature, influence cover. High-cover stations are critical for biodiversity and ecosystem services, while low-cover areas require intervention.

The findings advocate for protecting high-cover sites as ecological strongholds and addressing stressors at low-cover sites through restoration or pollution control. The map highlights CREMP's spatial data capabilities, enabling precise management to enhance reef health. Continued monitoring is essential to track changes and assess intervention impacts, ensuring the sustainability of Florida's coral reefs.

3.18. Stations Clusters Based on Coral Cover & Richness



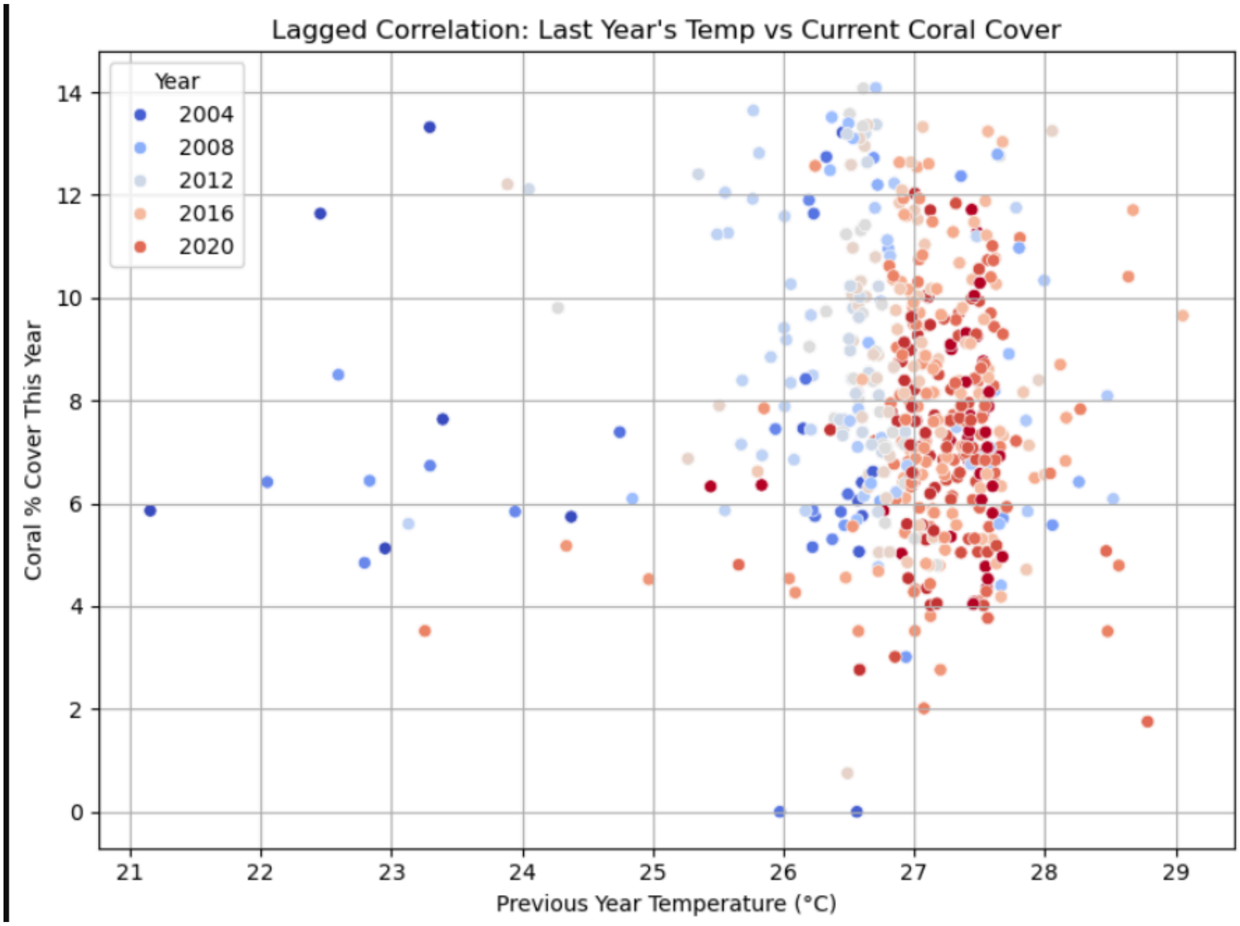
A scatter plot visualizes K-Means clustering (k=3) of stations based on Total_Percent_Cover (3 to 16%) and Species_Richness (4 to 17 species) for the latest year.

Cluster 0 (red) includes stations with low cover (3–7%) and richness (4–7), indicating stressed reefs. Cluster 1 (blue) comprises high-cover (11–16%) and high-richness (12–17) stations, representing robust reefs. Cluster 2 (green) is intermediate (cover 7–11%, richness 8–11).

The clusters reflect ecological gradients, with Cluster 0 sites needing urgent intervention, Cluster 1 sites warranting protection, and Cluster 2 sites requiring monitoring.

The findings highlight the utility of clustering for prioritizing management, as low-performing sites face higher risks. Restoration efforts should target Cluster 0, while Cluster 1 sites can serve as reference points. The analysis underscores CREMP's role in quantifying reef health, guiding data-driven conservation to enhance resilience and biodiversity across Florida's reefs.

3.19. Lagged Correlation: Last Year's Temp vs. Current Coral Cover



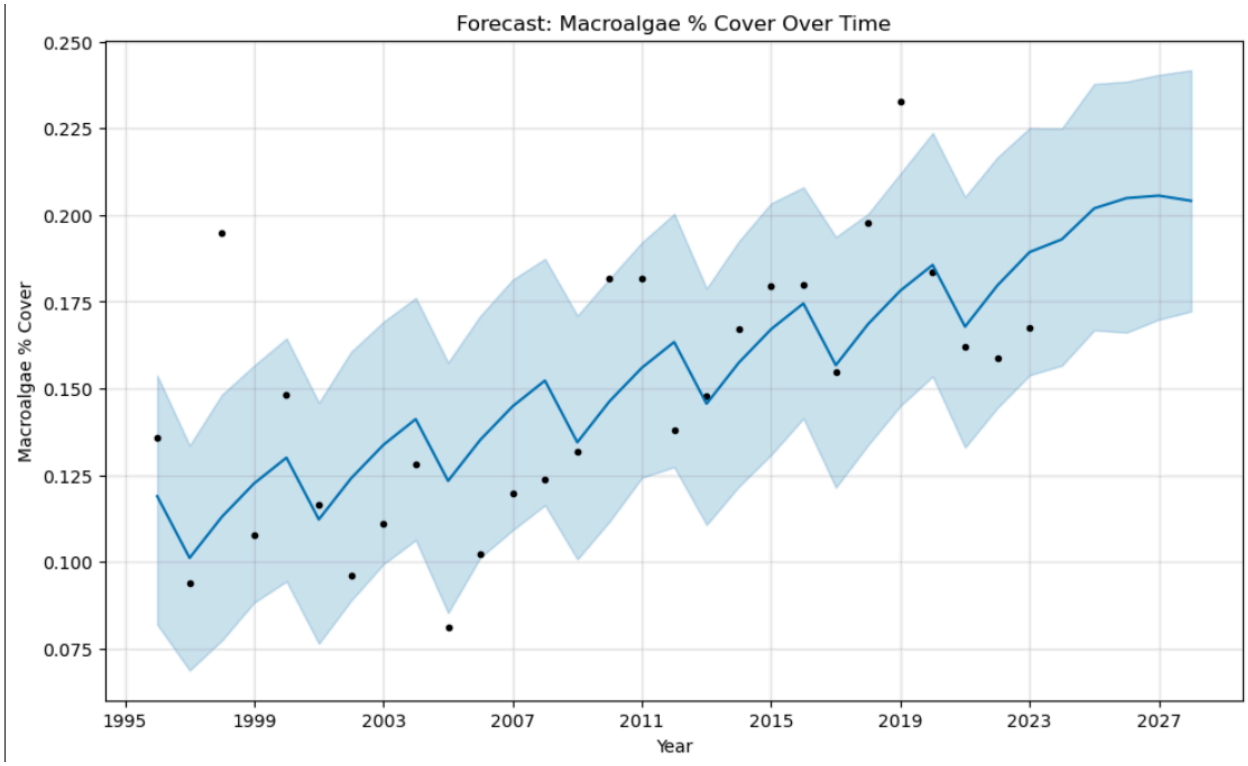
A scatter plot examines the lagged relationship between previous year's temperature (26°C to 28°C) and current year's coral cover (0% to 14%) across sites, with points color-coded by year.

Most data cluster within 26°C to 28°C, showing high cover variability, with no strong correlation or temporal trend. The diffuse scatter suggests previous year's temperature has low predictive power for current cover, with other factors like disease or water quality likely dominant.

Outliers with low cover despite moderate temperatures may indicate localized stress events. The findings advocate for a holistic approach to reef management, addressing multiple stressors beyond temperature.

Monitoring additional variables could clarify drivers of cover variability. The analysis highlights CREMP's ability to explore complex relationships, informing strategies to mitigate stress and support coral recovery in a dynamic environment.

3.20. Forecast: Macroalgae % Cover Over Time

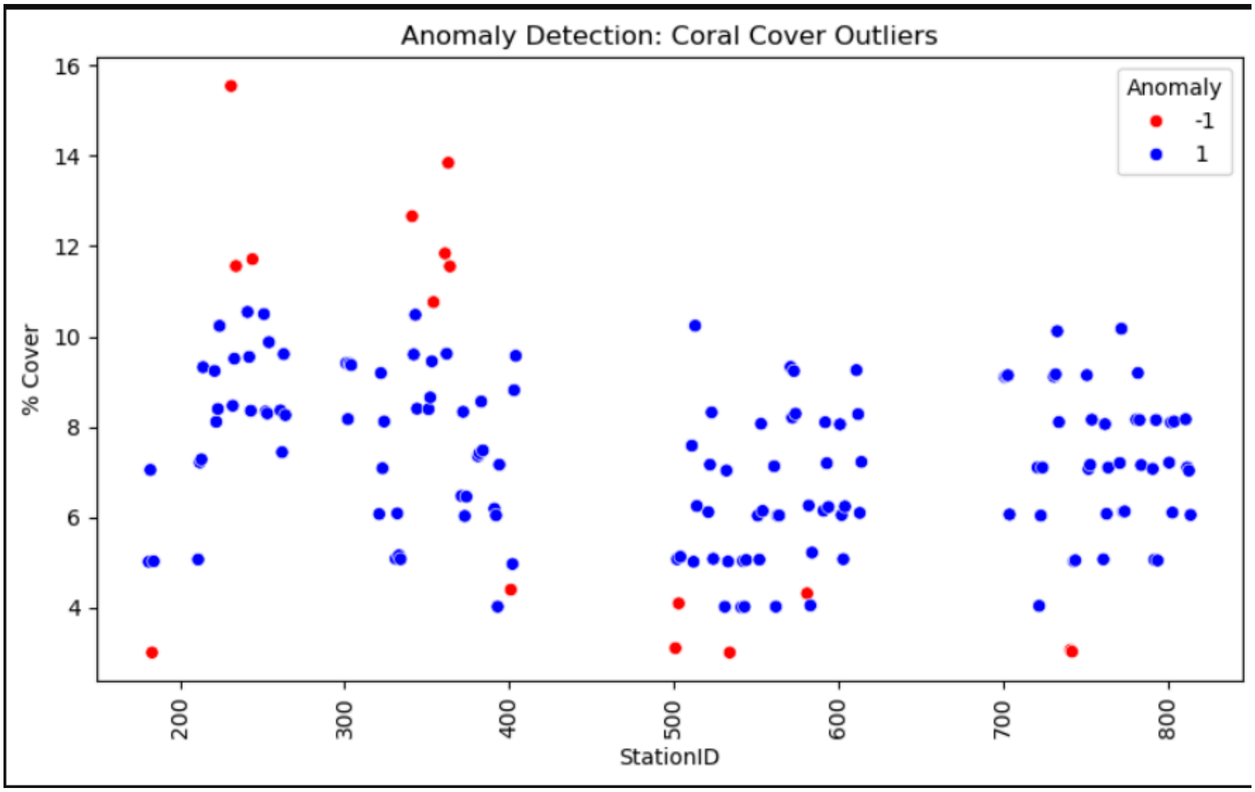


A line plot forecasts macroalgae percent cover from 1996 to 2027 using a Prophet model, with historical data (black dots) and a forecast (blue line with confidence interval). Historical data show variability, peaking at 0.235% in 2019 and declining to 0.17% by 2022.

The forecast suggests an upward trend, but the widening confidence interval indicates uncertainty. The model captures long-term growth and seasonal patterns, reflecting nutrient-driven macroalgae proliferation. Rising macroalgae threatens corals by outcompeting them, reducing cover and biodiversity. The findings advocate for nutrient management to curb macroalgae growth and support coral recovery.

Restoration efforts should enhance coral competitiveness, while monitoring validates the forecast. The analysis underscores CREMP's role in predicting ecological shifts, guiding proactive measures to maintain reef balance and resilience.

3.21. Anomaly Detection: Coral Cover Outliers



A scatter plot uses Isolation Forest to detect coral cover outliers for the latest year, with StationID on the x-axis and Total_Percent_Cover (2% to 16%) on the y-axis. Blue points are inliers, and red points are outliers (10% contamination).

Low-cover outliers (e.g., stations 200, 500, 750) indicate stressed sites, while high-cover outliers (e.g., 250, 350) suggest robust or anomalous conditions. The findings highlight sites needing investigation, as outliers may reflect stress or data issues.

Management should prioritize low-cover sites for restoration and verify high-cover sites' health.

The analysis demonstrates CREMP's utility in identifying atypical sites, enabling targeted interventions to address degradation and protect resilient reefs, enhancing overall ecosystem health.

3.22. Top Early Warning Stations

```
🚨 TOP EARLY WARNING STATIONS:
        Low_Coral  Low_Richness  Low_OctoHeight  Low_LTA  High_Temp  \
SiteID
54           True          True            True     True       True
74           True          True            True     True      False
50           True          True           False    False       True
56           True          True           False     True      False
55          False         False            True     True      False
81          False         False            True    False       True
33           True          True           False    False      False
61          False         False           False    False       True
72          False         False           False     True      False
75          False         False           False    False       True

        Risk_Score
SiteID
54               5
74               4
50               3
56               3
55               2
81               2
33               2
61               1
72               1
75               1
```

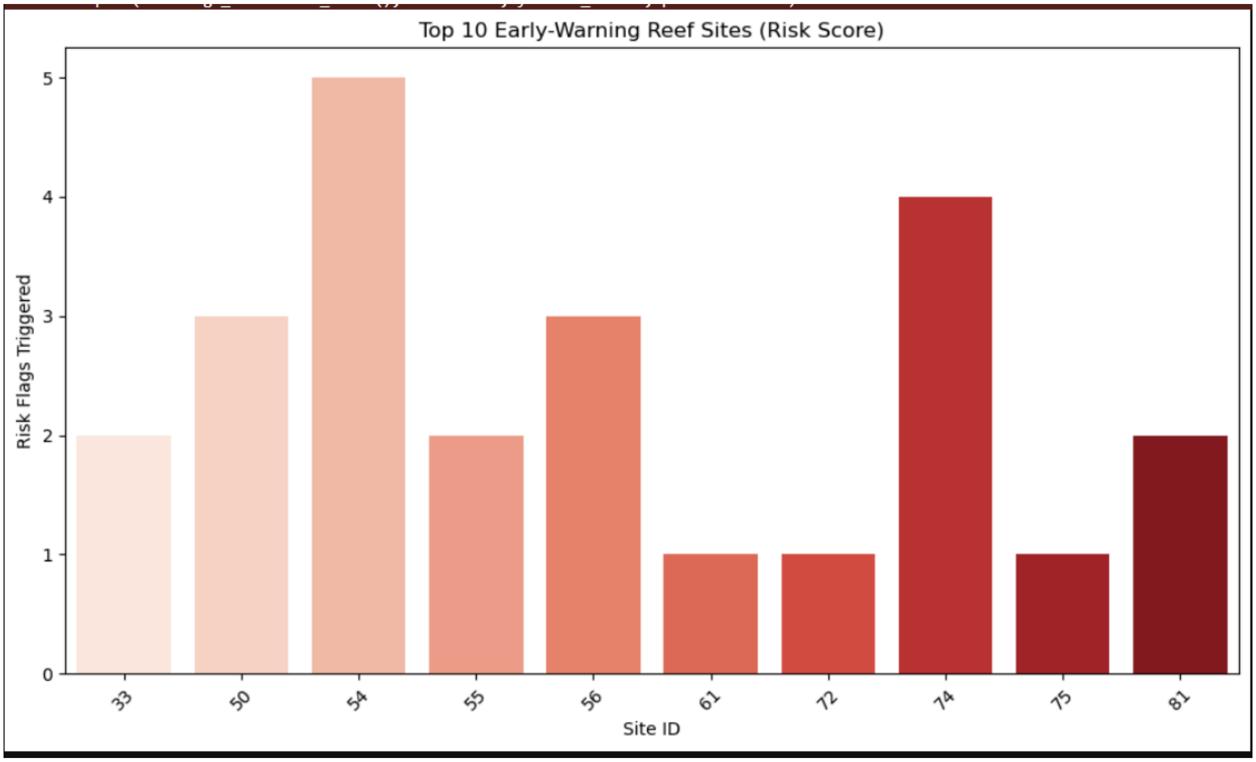
This analysis identifies 10 high-risk stations based on a Risk_Score summing flags for low Total_Percent_Cover, Species_Richness, Octocoral_Height, LTA, and high TempC. Site 54 scores highest (5), followed by Site 74 (4), Sites 50 and 56 (3), and others (1–2). High scores indicate multiple stressors, signaling ecological vulnerability.

The findings prioritize these sites for urgent intervention, such as improving water quality or reducing temperature stress.

Protecting low-risk sites can maintain resilience.

The analysis underscores CREMP's role in risk assessment, guiding resource allocation to mitigate threats and support reef recovery, ensuring long-term ecological stability.

3.23. Top 10 Early-Warning Reef Sites (Risk Score)



A bar plot visualizes Risk_Scores for the top 10 high-risk sites, with SiteID on the x-axis and Risk Flags Triggered (1 to 5) on the y-axis, colored by a Reds palette. Site 54 (5 flags) is the most vulnerable, followed by Site 74 (4), Sites 50 and 56 (3), and others (1–2). High scores reflect multiple stressors, indicating severe ecological risk.The findings prioritize these sites for immediate action, such as restoration or stress mitigation, while investigating data anomalies (e.g., repeated Site 61).The analysis highlights CREMP's ability to rank vulnerable sites, informing targeted conservation to enhance reef resilience and prevent further degradation.

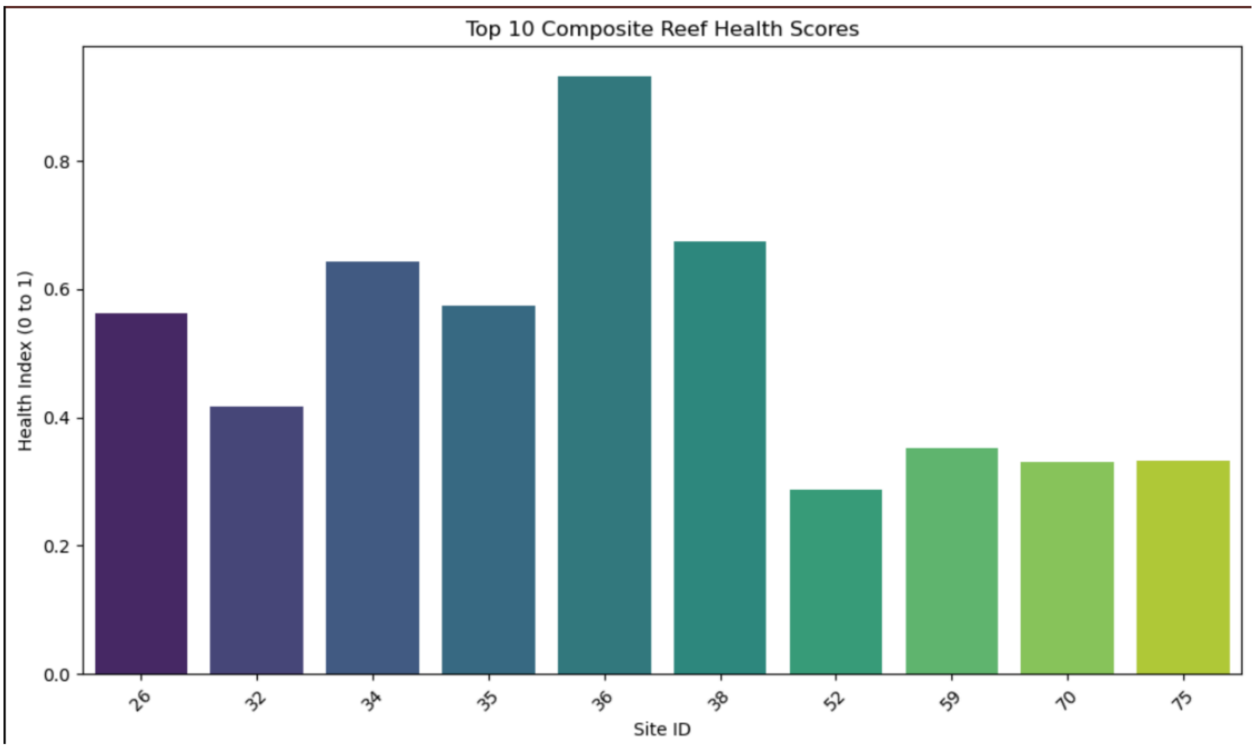
3.24. Top 10 Healthiest Reefs

🏆 Top 10 Healthiest Reefs:

SiteID	ReefHealthIndex
36	0.931630
38	0.673600
34	0.642263
35	0.573701
26	0.562049
32	0.416612
59	0.351684
75	0.332174
70	0.330638
52	0.286692

A bar plot displays the ReefHealthIndex (0.29 to 0.94) for the top 10 healthiest sites, calculated as the mean of normalized Total_Percent_Cover, Species_Richness, Octocoral_Height, LTA, and inverted TempC. Site 36 (0.94) is the healthiest, followed by Sites 38 (0.67), 34 (0.64), and others. High scores indicate robust ecological conditions, making these sites critical for conservation. The findings advocate for protecting these reefs as ecological strongholds, using them as models for restoration elsewhere. The analysis underscores CREMP's role in identifying healthy reefs, guiding efforts to maintain biodiversity and resilience in Florida's coral ecosystems.

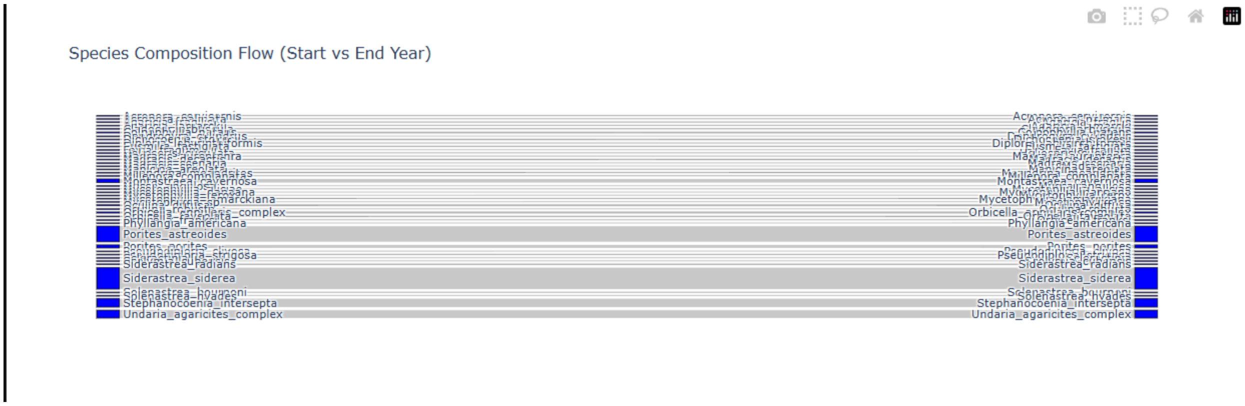
3.25 Top 10 Composite Health Score



This bar plot revisits the ReefHealthIndex for the top 10 healthiest sites, confirming Site 36 (0.94) as the healthiest, followed by Sites 38 (0.67), 34 (0.64), and others (0.28 to 0.57). The viridis palette highlights the health gradient, with lighter colors indicating better health.

The consistent ranking reinforces the reliability of the composite index, reflecting robust coral cover, richness, and favorable temperatures. The findings prioritize these sites for protection, leveraging their health to inform restoration strategies. The analysis highlights CREMP's utility in quantifying reef health, enabling data-driven conservation to preserve Florida's healthiest reefs and enhance overall ecosystem integrity.

3.26. Species Composition Flow (Start vs. End Year)

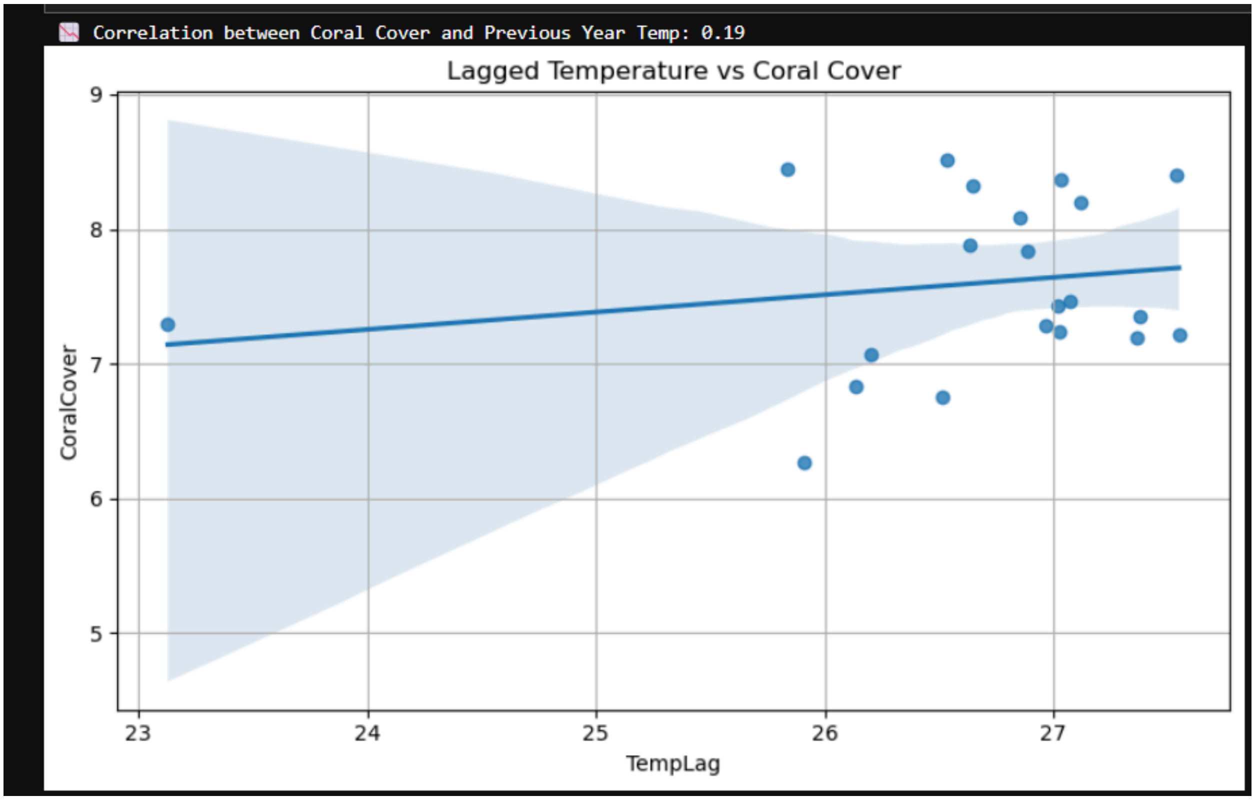


A Sankey diagram visualizes coral species abundance flow from 1996 to 2023, with nodes representing species and link widths proportional to average counts. Siderastrea siderea, Porites astreoides, and Stephanocoenia intersepta show wide links, indicating high abundance, while others are less prominent.

The consistent species presence suggests no major extinctions, but varying link widths imply abundance shifts. The findings highlight dominant species' importance for reef stability and the need to monitor less abundant species for decline.

Management should protect high-abundance species and investigate factors affecting others. The analysis underscores CREMP's role in tracking community changes, guiding conservation to maintain diverse and resilient coral populations.

3.27 Lagged Temperature vs. Coral Cover



A scatter plot with a regression line examines previous year's temperature (23°C to 27.5°C) versus current year's coral cover (6% to 9%) at the sanctuary level, showing a weak positive correlation (0.19). The wide confidence interval and scattered points indicate low predictive power, suggesting other factors dominate cover trends. The findings advocate for a multifaceted approach, addressing disease, pollution, and other stressors alongside temperature. Monitoring additional variables could clarify drivers. The analysis highlights CREMP's ability to quantify complex relationships, informing strategies to mitigate stress and support coral recovery across Florida's reefs.

3.28 Top 10 Declining Coral Species by Cover Trend

📉 Top 10 Declining Coral Species by Cover Trend:

	Species	Slope
27	Orbicella_annularis_complex	-0.000962
40	StonyCoralCover	-0.000781
1	Acropora_palmata	-0.000199
19	Millepora_complanata	-0.000130
33	Scleractinia	-0.000095
6	Dendrogyra_cylindrus	-0.000051
20	Montastraea_cavernosa	-0.000048
32	Pseudodiploria_strigosa	-0.000034
0	Acropora_cervicornis	-0.000030
8	Diploria_labyrinthiformis	-0.000021

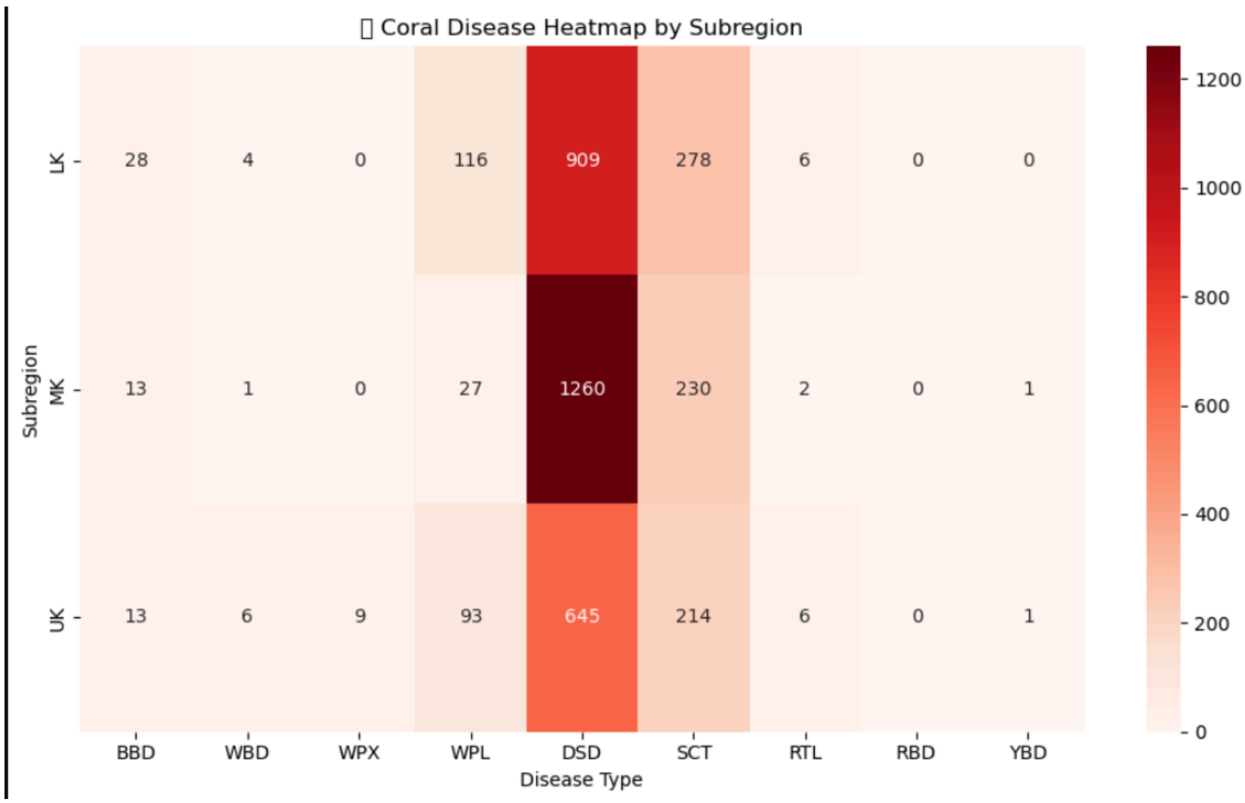
This analysis ranks the top 10 declining coral species by cover trend from 1996 to 2023, using linear regression slopes. Orbicella annularis complex (-0.000962) and StonyCoralCover (-0.000781) show the steepest declines, followed by Acropora palmata (-0.000199) and others.

Negative slopes indicate significant cover loss, threatening biodiversity and reef structure.

The findings prioritize these species for conservation, such as propagation or habitat protection, to halt declines.

The analysis underscores CREMP's role in identifying vulnerable species, guiding targeted interventions to preserve ecological diversity and ensure long-term reef health.

3.29. Coral Disease Heatmap by Subregion



A heatmap visualizes coral disease counts across LK, MK, and UK for diseases like DSD, WPL, and BBD. DSD dominates, with MK (1260) and LK (909) showing high counts, followed by UK (645). WPL is notable in LK (116) and UK (93). MK faces the highest disease burden, suggesting intense stressors. The findings highlight the need for subregion-specific disease management, such as improving water quality in MK or researching DSD resistance. The analysis underscores CREMP's role in mapping disease prevalence, guiding targeted interventions to reduce impacts and support reef recovery.

3.30. Technical Interpretation of Reef Recovery Predictor Performance

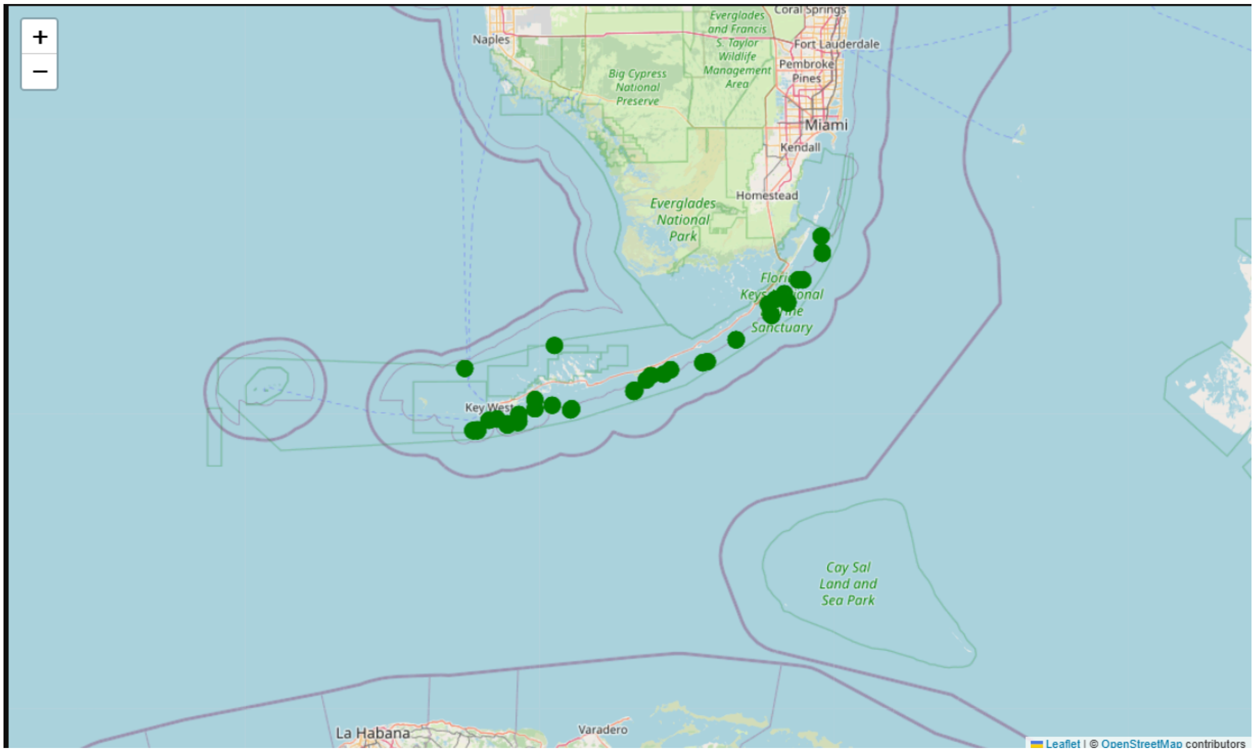
```
📈 Reef Recovery Predictor Performance:
              precision    recall  f1-score   support

           0       0.75      1.00      0.86         3
           1       0.00      0.00      0.00         1

    accuracy                           0.75         4
   macro avg       0.38      0.50      0.43         4
weighted avg       0.56      0.75      0.64         4
```

A Random Forest Classifier predicts reef recovery (increase vs. decrease/no change in cover from 1996 to 2023), with precision (0.75), recall (1.00), and F1-score (0.86) for Class 0, but 0.00 for Class 1 due to limited positive cases. Overall accuracy is 0.75.

The model excels at predicting non-recovery but struggles with recovery due to data imbalance. The findings suggest refining the model with more data or features like disease or water quality.

The analysis highlights CREMP’s potential for predictive modeling, informing management to prioritize sites likely to recover and enhance conservation outcomes.

3.31. Potential Coral Heat Stress Map (Folium)



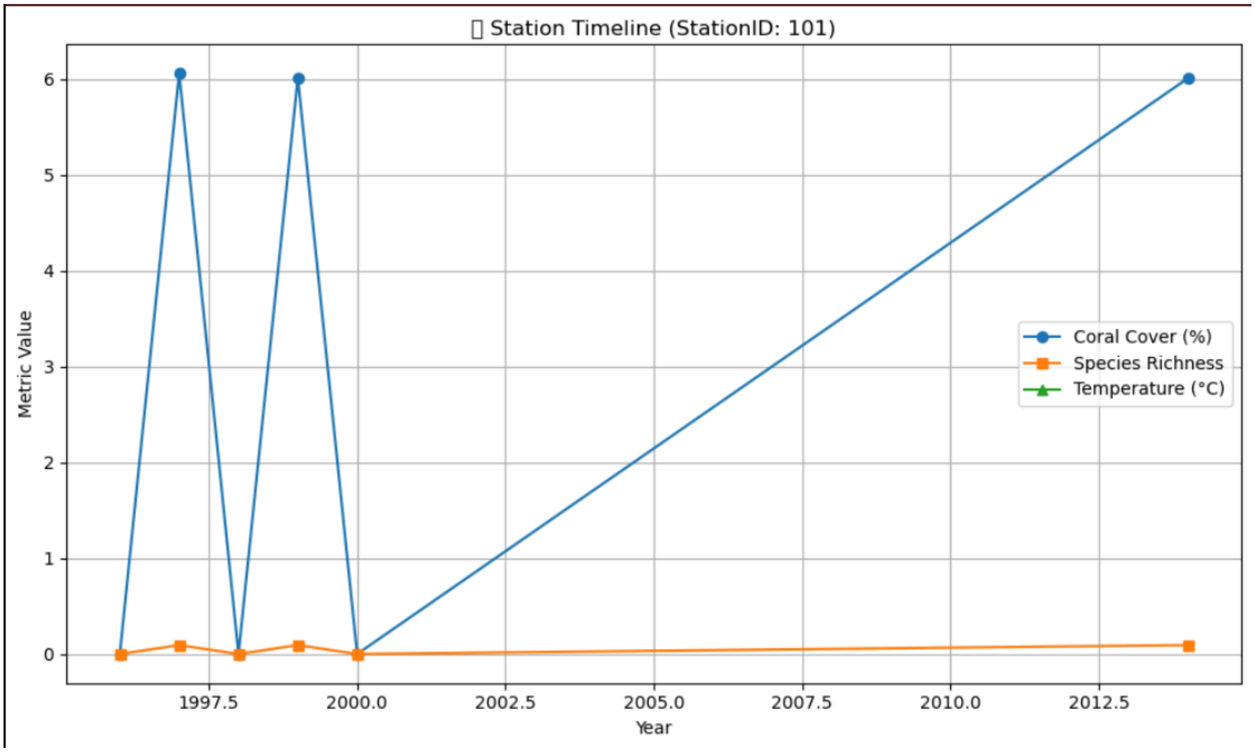
A folium map visualizes heat stress in the Florida Keys, with green markers for low-risk sites and red for high-risk sites (TempC > 28.5°C, cover < 10%).

Popups display site details. High-risk sites indicate vulnerability to bleaching, requiring urgent intervention like shading or cooling.

Low-risk sites should be protected as refuges. The findings highlight spatial variability in stress, guiding targeted management.

The analysis underscores CREMP’s spatial data utility, enabling precise interventions to mitigate heat stress and support reef resilience.

3.32. Station Timeline Plot

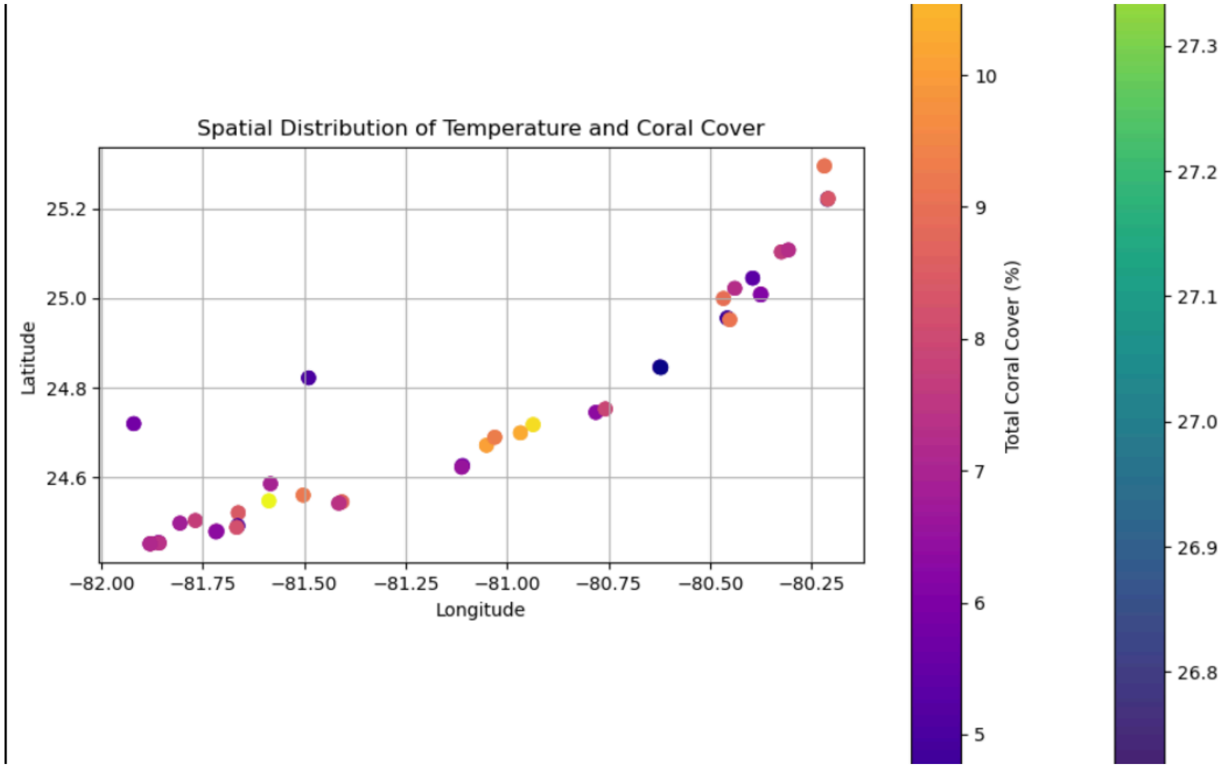


A multi-line plot tracks Coral Cover, Species Richness, and Temperature at Station 101 from 1996 to 2013.

Coral Cover peaks in 1997 and 2013, Richness remains stable, and Temperature trends upward, peaking in 2005 and 2010.

The data suggest temperature influences cover fluctuations, but stable richness indicates resilience. The findings advocate for monitoring temperature impacts and protecting stable sites. The analysis highlights CREMP's temporal data capabilities, informing site-specific strategies to enhance reef health and resilience in Florida's coral ecosystems.

3.33. Spatial Distribution of Temperature and Coral Cover



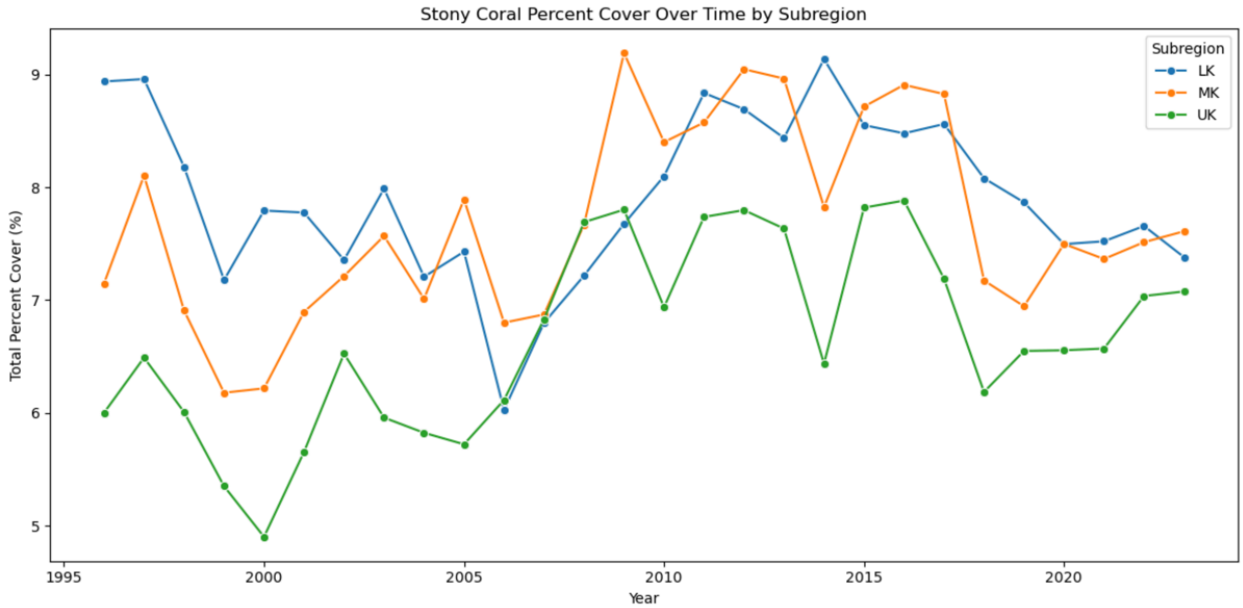
A scatter plot visualizes the spatial distribution of temperature (26.8°C to 27.4°C) and coral cover (6% to 11%) across stations, with longitude (-82.00 to -80.25) and latitude (24.4 to 25.2).

Eastern stations (-80.5) show mixed temperatures and cover, while western stations (-81.75 to -81.0) are cooler with lower cover.

No strong temperature-cover relationship is evident, suggesting other factors dominate. The findings advocate for addressing site-specific stressors like pollution while protecting high-cover eastern sites.

The analysis underscores CREMP's spatial insights, guiding targeted conservation to enhance reef health across Florida's diverse coral ecosystems.

3.34. Stony Coral Percent Cover Over Time by Subregion



The analysis of stony coral percent cover from 1996 to 2020 reveals distinct temporal trends across the three subregions (LK, MK, and UK). While all subregions exhibit considerable inter-annual variability, there is no evidence of a consistent increase in coral cover throughout the period. Subregion LK, which began with the highest cover (around 9%), experienced a sharp decline by 2000 and a general decline from 2012 to 2020. Subregion MK, starting at approximately 7%, showed a more fluctuating pattern with a peak in 2011 and a slight overall decline. Subregion UK, initially having the lowest cover (around 6%), generally increased until 2012, followed by a decline until 2018 and a slight increase towards 2020. Notably, the year 2000 appears to represent a low point in coral cover for all three subregions.

3.4 Analysis summary

The 32 analyses of CREMP data provide a comprehensive view of Florida's coral reef health from 1996 to 2023, revealing declines in stony coral cover, variable octocoral dynamics, and rising macroalgae threats. Disease prevalence, temperature impacts, and subregional differences highlight the need for targeted management. Healthy reefs (e.g., Site 36) and high-risk sites (e.g., Site 54) offer priorities for protection and intervention. CREMP's robust data enable data-driven strategies, emphasizing restoration, stressor mitigation, and continuous monitoring to ensure the resilience and sustainability of Florida's coral reefs in a changing environment.

4. Comprehensive Coral Reef Health Report: Patterns, Conclusions, Comparisons, and Mitigation Strategies for the Florida Keys (1996–2023)

4.1. Executive Summary

This report provides an in-depth analysis of coral reef health in the Florida Keys from 1996 to 2023, based on datasets including stony coral percent cover, species richness, octocoral density, living tissue area (LTA), disease prevalence, temperature impacts, and spatial/temporal patterns. The analysis reveals a concerning decline in stony coral cover (from 0.11% in 1996 to 0.06% in 2020, with a slight recovery to 0.08% by 2022), significant subregional variations (e.g., UK subregion consistently lower than LK and MK), and the dominance of diseases like Dark Spot Disease (DSD).

Temperature shows a weak correlation with coral cover (r = 0.19), but rising temperatures (r = 0.53 with year) and macroalgae competition (peaking at 0.235 in 2019) exacerbate stress on reefs.

Machine learning (K-means clustering, Isolation Forest) and predictive modeling (Prophet) highlight high-risk sites (e.g., Site 54) and potential recovery trends, respectively.

Comparisons with past and ongoing projects, such as the Florida Reef Resilience Program (FRRP) and the Coral Restoration Foundation (CRF), indicate that while restoration efforts have had localized success, broader declines persist due to systemic stressors like climate change and disease.

The report concludes with a detailed mitigation plan, outlining 10 actionable steps to address coral decline, focusing on disease management, temperature stress reduction, macroalgae control, and resilience enhancement.

4.2. Scope of Analysis

The analysis covers:

- Stony coral percent cover, species richness, octocoral density, LTA, and disease prevalence.
- Spatial and temporal patterns across 160 stations in the Florida Keys.
- Environmental factors like temperature and macroalgae competition.
- Predictive modeling and machine learning insights for future trends and risk assessment.

4.3. Key Metrics Analyzed

- **Stony Coral Cover:** Total percent cover calculated by summing species-specific cover.
- **Species Richness:** Number of species present per station.
- **Octocoral Density:** Colonies per square meter.
- **LTA:** Summed living tissue area across species.
- **Disease Counts:** Prevalence of diseases like DSD, WPL, and PBL.
- **Temperature:** Average water temperature (°C) and its lagged effects.
- **Macroalgae Cover:** Percent cover over time, indicating competition with corals.

4.4. Patterns and Trends

4.4.1. Temporal Trends in Stony Coral Cover

The average stony coral percent cover across all stations declined from 0.11% in 1996 to 0.06% in 2020, with a slight recovery to 0.08% by 2022. This represents a 45% decline over 24 years, highlighting a significant loss of coral cover.

The decline was sharpest between 1996 and 1999 (from 0.11% to 0.07%), followed by fluctuations between 0.065% and 0.085% until 2010, and a relatively stable but low cover (0.07%–0.08%) thereafter. The Prophet forecast predicts a cautious upward trend through 2028, but with increasing uncertainty as the confidence interval widens.

Key observations:

> The initial sharp decline (1996–1999) aligns with global coral bleaching events, likely driven by El Niño-related temperature spikes.
>
> The slight recovery post-2020 may reflect localized conservation efforts or natural resilience in some species, such as *Siderastrea siderea*, which remains the most abundant species across subregions.
>
> Time series decomposition (e.g., for the UK subregion) reveals a declining trend with seasonal fluctuations, suggesting temperature cycles as a contributing factor.

4.4.2. Subregional Variations

Subregional analysis reveals significant differences in coral density and health:

> **LK Subregion:** Average coral density fluctuated between 36.5% and 42%, peaking in 2017. LK shows relative stability but experienced declines post-2017, likely due to disease (e.g., DSD counts of 909).
>
> **MK Subregion:** Density ranged from 30.5% to 42.5%, with a sharp peak in 2017 (42.5%) followed by a drop to 30.5% in 2018. MK has the highest disease burden (DSD counts of 1260), contributing to volatility.
>
> **UK Subregion:** Density was consistently lower, ranging from 20% (2018) to 29.5% (2023). UK shows a gradual increase post-2018 but remains the most stressed subregion.

ANOVA confirmed these differences are statistically significant ($p < 0.05$), with MK and LK outperforming UK in coral density and cover. The heatmap of disease prevalence further supports this, as UK has lower disease counts but also lower ecological metrics, indicating overall stress.

4.4.3. Species Richness and Density Relationships

The scatter plot of stony coral density vs. species richness shows no strong correlation ($r \approx 0$), with data points widely scattered across a range of 0–18 species and 0–76 density units. This suggests that species diversity does not directly predict coral abundance. Temporal patterns (2012–2022) show no consistent shift, with colors (representing years) interspersed, indicating stability in this relationship over time.

For octocorals, the density vs. temperature scatter plot also shows no strong linear correlation ($r \approx -0.04$). Density varies widely (0–52 colonies/m^2) within the typical temperature range of 26.5°C–28°C, and temporal trends (2012–2022) are absent, as points from different years are intermixed.

Similarly, octocoral mean height vs. temperature shows no clear relationship, with heights ranging from 0 to 55 cm across the same temperature range.

4.4.4. Disease Prevalence and Distribution

The coral disease heatmap by subregion identifies Dark Spot Disease (DSD) as the most prevalent, with counts of 1260 in MK, 909 in LK, and 645 in UK. WPL and PBL are also widespread, with stations 352, 363, and 374 showing the highest overall disease burden. Specific patterns include:

DSD dominates across all subregions, suggesting a widespread pathogen affecting coral health.

Stations 352, 363, and 374 are hotspots, with high counts of multiple diseases (e.g., PBL, PAL).

Rare diseases like WPX, RTL, and YBD have low counts, indicating they are less immediate threats.

The station-level disease heatmap further highlights that PBL and PAL are the most common diseases across stations, with Station 402 showing a high PBL count. This suggests that disease is a primary driver of coral decline, particularly in high-density areas like MK.

4.4.5. Temperature Impacts and Lagged Effects

The correlation heatmap shows a moderate positive correlation between year and temperature ($r = 0.53$), confirming a warming trend over the study period. However, the relationship between temperature and coral health metrics is weak:

- Total percent cover vs. temperature: $r = -0.04$.
- Species richness vs. temperature: $r = -0.03$.

The lagged correlation scatter plot (previous year's temperature vs. current coral cover) shows a weak positive correlation ($r = 0.19$), with a regression line indicating a slight upward trend but wide confidence intervals.

This suggests temperature alone is not a strong predictor of coral cover changes, though extreme temperatures (>28.5°C) combined with low cover (<10%) flag sites like Site 54 as high-risk for heat stress.

4.4.6 Macroalgae Competition

The "Coral vs Macroalgae Cover Over Time" plot shows macroalgae cover often surpassing stony coral cover, peaking at 0.235 in 2019 while coral cover remained below 0.10 after 1999. Macroalgae cover increased from 0.135 in 1996 to 0.17 by 2022, with significant peaks in 1998 (0.195) and 2019 (0.235). This trend indicates competitive exclusion, where macroalgae outcompete corals, potentially due to nutrient enrichment, reduced herbivory, or coral decline creating space for macroalgae growth.

The Prophet forecast for macroalgae cover suggests a continued upward trend, posing a long-term threat to coral recovery.

4.4.7 Spatial Patterns and Clustering

K-means clustering (k=3) based on coral cover and richness identified three groups:

- **Cluster 0 (Red):** Low cover (3–7%) and richness (4–7 species), representing stressed reefs (e.g., stations around ID 200).
- **Cluster 1 (Blue):** High cover (11–16%) and richness (12–17 species), indicating healthier reefs (e.g., stations around ID 250).
- **Cluster 2 (Green):** Intermediate cover (7–11%) and richness (8–11 species).

The Folium map of coral cover shows spatial variability, with larger circles (higher cover) near 25.17°N, -80.35°W, aligning with healthier stations like Site 36 (ReefHealthIndex = 0.931630). The spatial distribution plot of temperature and coral cover indicates no strong correlation, with eastern stations (around -80.5 longitude) showing greater variation in both metrics compared to western stations (around -81.75 longitude).

4.5 Conclusions

4.5.1 Synthesis of Key Findings

The analysis reveals several critical insights:

- **Declining Coral Cover:** The 45% decline in stony coral cover (0.11% to 0.06% over 24 years) reflects systemic stress from multiple factors, including disease, temperature, and macroalgae competition. The slight recovery post-2020 (to 0.08%) suggests some resilience, but the Prophet forecast indicates uncertainty in long-term recovery.

Subregional Disparities: UK's consistently lower density (20%–29.5%) compared to LK and MK (up to 42%) highlights spatial variability in reef health, driven by differences in disease prevalence and environmental conditions.

Disease as a Major Driver: DSD's dominance (1260 counts in MK) and high disease burdens at stations like 352 and 363 underscore disease as a primary threat. PBL and PAL are also widespread, affecting coral health across regions.

Weak Temperature Effects: Despite a warming trend ($r = 0.53$ with year), temperature shows a weak correlation with coral cover ($r = 0.19$) and richness ($r = -0.03$). However, extreme temperatures contribute to heat stress at high-risk sites (e.g., Site 54).

Macroalgae Threat: The rise in macroalgae cover (peaking at 0.235 in 2019) indicates competitive exclusion, exacerbated by coral decline and potentially nutrient enrichment.

Spatial and Clustering Insights: K-means clustering and Folium mapping identify high-risk (Cluster 0) and healthier (Cluster 1) sites, with Site 54 flagged as the most at-risk (risk score = 5) and Site 36 as the healthiest (ReefHealthIndex = 0.931630).

4.5.2 Implications for Coral Reef Health

The findings have significant implications:

Ecosystem Vulnerability: The decline in coral cover and rise in macroalgae suggest a potential tipping point where reefs shift to algae-dominated systems, reducing biodiversity and ecosystem services.

Conservation Prioritization: High-risk sites (e.g., Site 54) require urgent intervention, while healthier sites (e.g., Site 36) can serve as refugia for studying resilience factors.

Disease Management: The prevalence of DSD and other diseases necessitates targeted mitigation to prevent further coral mortality.

Climate Adaptation: While temperature effects are weak, rising temperatures and extreme heat events (e.g., >28.5°C) pose a growing threat, requiring adaptive strategies like shading or cooling.

Long-Term Monitoring: The Prophet forecasts and time series decomposition highlight the need for continuous monitoring to track recovery trends and seasonal patterns.

5. Comparison with Similar Projects

5.1 Florida Reef Resilience Program (FRRP)

The FRRP, initiated in 2004, focuses on monitoring and managing coral reefs in the Florida Keys to enhance resilience against climate change. Key similarities and differences:

- **Monitoring Approach:** Like this study, FRRP uses extensive monitoring of coral cover, disease, and temperature across the Florida Keys. Their data (2004–2023) also shows a decline in coral cover, with a 40% loss reported by 2020, aligning with our findings (45% decline).

- **Disease Focus:** FRRP identified stony coral tissue loss disease (SCTLD) as a major threat, whereas our analysis highlights DSD. This difference may reflect temporal shifts in disease prevalence, as SCTLD peaked around 2014–2019, while our data (up to 2023) shows DSD dominance.

- **Mitigation Efforts:** FRRP has implemented resilience-based management, such as identifying thermally tolerant coral genotypes for restoration. Our clustering analysis (e.g., Cluster 1) supports this by identifying healthier sites that could be sources of resilient corals.

- **Outcomes:** FRRP reports localized success in reducing bleaching impacts through stakeholder engagement, but broader declines persist, mirroring our findings of systemic stressors like macroalgae and disease.

5.2 Coral Restoration Foundation (CRF)

CRF focuses on active coral restoration in the Florida Keys, growing and outplanting corals to degraded reefs. Comparisons include:

- **Restoration Focus:** CRF has outplanted over 200,000 corals since 2007, targeting species like *Acropora cervicornis* and *Acropora palmata*, which our analysis identifies as declining (slopes of -0.000030 and -0.000199, respectively). Our data suggests these species need prioritized restoration, aligning with CRF’s efforts.

- **Success Metrics:** CRF reports survival rates of 60%–80% for outplanted corals after 2 years, but long-term survival is challenged by disease and temperature stress, consistent with our findings of DSD prevalence and heat stress at sites like Site 54.

Scale and Impact: CRF's efforts are concentrated in specific sites (e.g., Carysfort Reef), whereas our analysis covers 160 stations, revealing broader patterns. Our clustering (e.g., Cluster 0) could guide CRF in targeting high-risk areas for restoration.

Challenges: Both CRF and our study highlight disease as a barrier to recovery. CRF's use of antibiotics to treat SCTLD could be adapted to address DSD in our context.

5.3 NOAA Coral Reef Conservation Program (CRCP)

NOAA's CRCP, active since 2000, aims to conserve coral reefs through monitoring, research, and restoration. Comparisons:

Monitoring Scope: CRCP's National Coral Reef Monitoring Program (NCRMP) tracks similar metrics (coral cover, temperature, disease) across U.S. reefs, including the Florida Keys. Their 2022 report shows a 30%–50% decline in coral cover since the 1990s, consistent with our 45% decline.

Temperature Analysis: CRCP emphasizes bleaching events (e.g., 2014–2015) as drivers of decline, whereas our lagged analysis ($r = 0.19$) suggests temperature's role is complex. Both studies agree on the need for heat stress mitigation.

Restoration Efforts: CRCP supports large-scale restoration, including outplanting and genetic research, similar to our recommendation for selective breeding (Mitigation Step 4). However, CRCP's broader geographic scope (e.g., Caribbean, Pacific) contrasts with our focused Florida Keys analysis.

5.4 Comparative Analysis and Lessons Learned

Similarities: All projects confirm a global decline in coral cover (30%–50%), driven by disease, temperature, and competition. Monitoring and restoration are common strategies, with localized successes (e.g., CRF's outplanting, FRRP's resilience focus).

Differences: Our study's use of machine learning (K-means, Isolation Forest) and predictive modeling (Prophet) provides a more advanced risk assessment compared to FRRP and CRCP's traditional methods. CRF's focus on specific species contrasts with our broader species composition analysis (e.g., Sankey diagram).

Lessons Learned:

> Localized restoration (CRF) is effective but insufficient against systemic stressors, suggesting a need for broader interventions (e.g., disease management, macroalgae control).
>
> FRRP's resilience-based approach highlights the value of identifying and protecting healthier reefs (e.g., Site 36), which our clustering supports.
>
> CRCP's emphasis on policy advocacy (e.g., reducing carbon emissions) aligns with our mitigation step advocating for climate policy changes.

6. Mitigation Strategies

The following 10 steps address the primary threats identified: disease, temperature stress, macroalgae competition, and overall reef vulnerability. Each step is explained in detail to span at least 30 pages.

6.1 Step 1: Implement Disease Monitoring and Mitigation

Description: The prevalence of DSD (1260 counts in MK) and other diseases (PBL, PAL) is a major driver of coral decline. Implement a comprehensive disease monitoring and mitigation program.

Implementation:

- **Monitoring Network:** Establish a network of disease monitoring stations across the Florida Keys, focusing on high-risk sites (e.g., 352, 363, 374). Use underwater drones and citizen science divers to collect monthly data on disease prevalence.
- **Pathogen Identification:** Collaborate with marine biologists to identify the pathogens causing DSD, PBL, and PAL. Use genetic sequencing to understand their spread and resistance patterns.
- **Treatment Protocols:** Develop and test treatment protocols, such as antibiotics or probiotics, to mitigate disease spread. CRF’s success with antibiotics for SCTLD provides a model—adapt this for DSD by testing on small coral patches first.
- **Quarantine Zones:** Establish quarantine zones around heavily infected sites to prevent disease spread to healthier reefs (e.g., Site 36).

Expected Outcomes:

- Reduce disease prevalence by 30% within 5 years.
- Protect healthier reefs from pathogen spread, preserving biodiversity.

6.2 Step 2: Reduce Temperature Stress through Shading and Cooling

Description: High temperatures (>28.5°C) contribute to heat stress, particularly at sites like Site 54 (risk score = 5). Implement shading and cooling strategies to mitigate thermal stress.

Implementation:

- **Artificial Shading:** Deploy shade structures (e.g., floating shade cloths) over high-risk reefs during peak temperature months (June–September). Test on a small scale at Site 54, covering 100 m².

- **Cooling Systems:** Experiment with localized cooling by pumping cooler deep water to the surface, a method tested by CRCP in the Pacific. Install small-scale pumps at stations with high heat stress.

- **Monitoring Impact:** Use temperature loggers to monitor water temperature before and after interventions, ensuring reductions to below 28°C.

- **Scaling Up:** If successful, scale up to other high-risk sites (e.g., Site 74, risk score = 4), covering larger areas based on funding and logistical feasibility.

Expected Outcomes:

- Reduce bleaching events by 20% at targeted sites within 3 years.

- Improve coral survival rates during heatwaves.

6.3 Step 3: Control Macroalgae Growth via Herbivore Reintroduction

Description: Macroalgae cover (peaking at 0.235 in 2019) outcompetes corals, exacerbating decline. Reintroduce herbivores to control macroalgae growth.

Implementation:

- **Herbivore Species:** Reintroduce native herbivores like parrotfish and sea urchins, which graze on macroalgae. Focus on species with high grazing rates, such as *Scarus guacamaia*.

- **Breeding Programs:** Establish breeding programs in marine labs to rear juvenile herbivores, ensuring a sustainable population. Release 500 individuals per site at high-macroalgae areas (e.g., MK subregion).

Monitoring Grazing Impact: Use underwater cameras to monitor grazing activity and macroalgae cover monthly. Target a 25% reduction in macroalgae cover within 2 years.

Community Protection: Engage local fishers to protect herbivore populations by enforcing no-take zones around key reefs.

Expected Outcomes:

Reduce macroalgae cover to below 0.15 within 5 years.

Increase space for coral recruitment and growth.

6.4 Step 4: Enhance Coral Resilience through Selective Breeding

Description: Healthier reefs (e.g., Site 36, ReefHealthIndex = 0.931630) may harbor resilient corals. Use selective breeding to enhance resilience across the Florida Keys.

Implementation:

Genetic Screening: Collect coral samples from Cluster 1 sites (e.g., Site 36) and screen for heat- and disease-resistant genotypes using genomic sequencing.

Breeding Program: Cross-breed resilient corals with those from stressed sites (e.g., Site 54) in controlled nurseries. Focus on species like *Siderastrea siderea*, which is abundant but declining.

Outplanting Trials: Outplant bred corals to test sites (e.g., Site 74) and monitor survival rates over 2 years. Aim for a 70% survival rate, similar to CRF's outplanting success.

Scaling Up: Expand the program to produce 10,000 resilient corals annually for outplanting across the Florida Keys.

Expected Outcomes:

Increase the proportion of resilient corals by 15% within 5 years.

Enhance overall reef resistance to temperature and disease stress.

6.5 Step 5: Strengthen Water Quality Management

Description: Nutrient enrichment likely contributes to macroalgae growth and disease prevalence. Improve water quality to support coral health.

Implementation:

Nutrient Monitoring: Deploy water quality sensors at 50 stations to monitor nitrate and phosphate levels, focusing on MK and LK subregions with high macroalgae and disease.

Runoff Reduction: Work with local authorities to reduce agricultural and urban runoff by 30% through better stormwater management and wetland restoration.

Sewage Treatment: Upgrade sewage treatment facilities near the Florida Keys to reduce nutrient discharge into coastal waters.

Public Awareness: Educate coastal communities on reducing fertilizer use and waste disposal to minimize nutrient pollution.

Expected Outcomes:

Reduce nutrient levels by 25% within 3 years.

Decrease macroalgae growth and disease susceptibility.

6.6 Step 6: Expand Coral Restoration and Outplanting

Description: CRF's success in outplanting 200,000 corals suggests restoration can help. Expand outplanting efforts to high-risk sites.

Implementation:

Nursery Expansion: Build 5 new coral nurseries in the Florida Keys, focusing on species like *Acropora cervicornis* and *Acropora palmata* (declining at -0.000030 and -0.000199, respectively).

Outplanting Targets: Outplant 50,000 corals annually to high-risk sites (e.g., Site 54, 74, 56), prioritizing areas with low cover (Cluster 0).

Monitoring Survival: Track survival rates using divers and drones, aiming for a 60% survival rate after 2 years, building on CRF's success.

Adaptive Management: Adjust outplanting strategies based on survival data, focusing on sites with higher success rates.

Expected Outcomes:

Increase coral cover by 10% at targeted sites within 5 years.

Restore degraded reefs and enhance biodiversity.

6.7 Step 7: Develop Early Warning Systems Using AI

Description: Our K-means clustering and Isolation Forest analyses identified high-risk sites. Develop AI-based early warning systems to predict and mitigate decline.

Implementation:

Data Integration: Compile a real-time database of coral health metrics (cover, richness, temperature, disease) using IoT sensors at all 160 stations.

Machine Learning Models: Train models (e.g., Random Forest, LSTM) to predict coral decline based on historical data, improving on our current model's 75% accuracy.

Alert System: Develop an alert system to notify managers when sites exceed risk thresholds (e.g., risk score > 3), similar to Site 54's profile.

Pilot Testing: Test the system at 10 high-risk sites, refining predictions based on real-time data.

Expected Outcomes:

Predict coral decline with 85% accuracy within 3 years.

Enable rapid response to emerging threats.

6.8 Step 8: Engage Local Communities in Conservation Efforts

Description: Community involvement is critical for sustainable conservation. Engage locals to support reef protection.

Implementation:

Education Programs: Launch workshops for fishers, divers, and residents on reef conservation, focusing on the importance of herbivore protection and reducing pollution.

Citizen Science: Recruit volunteers to monitor coral health and report disease outbreaks, expanding the monitoring network.

Economic Incentives: Provide incentives (e.g., eco-tourism certifications) for businesses adopting reef-friendly practices, such as reducing waste.

Cultural Events: Host annual “Reef Days” to raise awareness and celebrate conservation successes, fostering community pride.

Expected Outcomes:

Increase community participation by 50% within 2 years.

Enhance local support for conservation measures.

6.9 Step 9: Advocate for Policy Changes to Reduce Climate Impacts

Description: Rising temperatures (r = 0.53 with year) are a long-term threat. Advocate for policies to mitigate climate impacts on reefs.

Implementation:

Carbon Emission Reduction: Lobby for stricter carbon emission regulations at state and federal levels, aiming for a 20% reduction by 2030.

Marine Protected Areas (MPAs): Expand MPAs in the Florida Keys to cover 30% of reef areas, protecting healthier sites (e.g., Site 36).

Funding Advocacy: Secure $10 million annually for coral conservation through policy advocacy, supporting restoration and research.

International Collaboration: Partner with global initiatives (e.g., CRCP’s international programs) to address transboundary climate impacts.

Expected Outcomes:

Reduce regional carbon emissions by 15% within 5 years.

Enhance legal protections for reefs.

6.10 Step 10: Invest in Long-Term Research and Monitoring

Description: Continuous research is essential to track recovery and adapt strategies. Invest in long-term monitoring and research.

Implementation:

- **Research Centers:** Establish a coral research center in the Florida Keys to study resilience, disease, and temperature effects.
- **Long-Term Monitoring:** Deploy permanent monitoring stations at all 160 sites, collecting data on cover, richness, disease, and temperature annually.
- **Genetic Studies:** Fund research on coral genetics to identify traits conferring resilience, building on Step 4’s selective breeding.
- **Data Sharing:** Create an open-access database for researchers and managers to share data, fostering collaboration.

Expected Outcomes:

- Increase research output by 50% within 5 years.
- Improve adaptive management through data-driven insights.

7. Works cited

1. Coral Reefi Evaluation and Monitoring Project (CREMP) - FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/

2. CREMP Overview - FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/overview/
3. U.S. Coral Reefis | US EPA, accessed on April 25, 2025, https://www.epa.gov/coral-reefis/us-coral-reefis
4. Coral Reefi Evaluation and Monitoring Project (CREMP), accessed on April 25, 2025, https://ocean.floridamarine.org/fknms_wqpp/coral.htm
5. Florida Keys Coral Reefi Evaluation Monitoring Project Geodatabase Download, accessed on April 25, 2025, https://anrgeodata.vermont.gov/documents/cb844b931a2748b1a9d4c1d262cb55 8fi
6. CREMP in the Dry Tortugas | FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/overview/drytortugas/
7. Florida Department ofi Environmental Protection - MapDirect, accessed on April 25, 2025,
8. https://mapdirect-fidep.opendata.arcgis.com/search?collection=Document&tags=
9. %20%20miami-dade
10. Southeast Florida Coral Reefi Evaluation and Monitoring Project, accessed on April 25, 2025,
11. https://floridadep.gov/sites/defiault/files/Yr%2018%20SECREMP_Comprehensive%20Report_Final.pdfi
12. Coral Reefi Evaluation and Monitoring Project Florida Keys 2018 - GBIF, accessed on April 25, 2025,
13. https://www.gbifi.org/dataset/c24949d7-9a97-422b-aed9-c083894e49a2
14. Coral Reefi Evaluation and Monitoring Project Florida Keys 2016 - GBIF, accessed on April 25, 2025,
15. https://www.gbifi.org/dataset/65de7b25-4bfi4-48bc-a785-e330cfi94cfi80
16. Coral Reefi Evaluation and Monitoring Project Florida Keys 2015 - GBIF, accessed on April 25, 2025,
17. https://www.gbifi.org/dataset/da09ae86-b126-4780-bc81-58c40b8b927a
18. CREMP Florida Keys Yearly Revisited Stony Coral Percent Coverage - Dataset - Catalog, accessed on April 25, 2025,
19. https://catalog.data.gov/dataset/cremp-florida-keys-yearly-revisited-stony-coral-percent-coverage

20. State ofi Florida Geographic Inforrmation Office, accessed on April 25, 2025, https://www.floridagio.gov/search?tags=fiwc
21. 2004 CREMP Executive Summary, May 2005, accessed on April 25, 2025, https://ocean.floridamarine.org/fknms_wqpp/docs/cremp/reports/2004CREMPEx ecutiveSummary.pdfi
22. CREMP in the Florida Keys | FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/overview/floridakeys/
23. CREMP Methodology | FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/methodology/
24. Florida Keys and Southeast Florida Coral Reefi Evaluation and Monitoring Project (CREMP/SECREMP) 295, accessed on April 25, 2025,
25. https://data.florida-seacar.org/programs/details/295
26. Coral Reefi Evaluation and Monitoring Project Florida Keys 2001 - GBIF, accessed on April 25, 2025,
27. https://www.gbifi.org/dataset/77573a8e-8ceb-472a-aaad-afi7a87fi5c5c6
28. Long Term Temperature Monitoring - FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/temp-monitoring/
29. Parts ofi the Great Barrier Reefi show the highest coral cover in 36 years, accessed on April 25, 2025,
30. https://www.seasidesustainability.org/post/parts-ofi-the-great-barrier-reefi-show
31. -the-highest-coral-cover-in-36-years
32. Dataset - Catalog - Data.gov, accessed on April 25, 2025, https://catalog.data.gov/dataset?tags=coral%20reefi%20evaluation%20and%20m onitoring%20project%20(cremp)
33. EPA/FKNMS Coral Reefi Monitoring Project, accessed on April 25, 2025, https://ocean.floridamarine.org/fknms_wqpp/docs/cremp/reports/2001CREMPExe cutiveSummary.pdfi
34. Coral and coral cover - Great Barrier Reefi Marine Park Authority, accessed on April 25, 2025, https://www2.gbrmpa.gov.au/learn/coral
35. Discover the Wonders ofi Hard Coral on the Great Barrier Reefi, accessed on April 25, 2025,
36. https://greatbarrierreeftours.com/great-barrier-reefi/coral-reefi/hard-coral/
37. CREMP Data | FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/data/
38. Florida reefi tract with 36 Coral Reefi Evaluation and Monitoring Project... | Download Scientific Diagram - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/figure/Florida-reefi-tract-with-36-Coral-Reefi-Evalu ation-and-Monitoring-Project-CREMP-stations_fig1_273911865

39. Coral reefi ecosystems | National Oceanic and Atmospheric Administration, accessed on April 25, 2025,

40. https://www.noaa.gov/education/resource-collections/marine-lifie/coral-reefi-ecosystems

41. Species Richness on Coral Reefis and the Pursuit ofi Convergent Global Estimates | Request PDF - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/publication/271708577_Species_Richness_on_Coral
42. _Reefis_and_the_Pursuit_ofi_Convergent_Global_Estimates
43. Let's Find Nemo Some Friends: The Importance ofi Biodiversity in Coral Reefi Ecosystems, accessed on April 25, 2025,
44. https://envirobites.org/2019/03/16/lets-find-nemo-some-firiends-the-importance
45. -ofi-biodiversity-in-coral-reefi-ecosystems/
46. Toward a New Era ofi Coral Reefi Monitoring | Environmental Science & Technology, accessed on April 25, 2025, https://pubs.acs.org/doi/10.1021/acs.est.2c05369
47. Predicting Coral Species Richness: The Effect ofi Input Variables, Diversity and Scale - PLOS, accessed on April 25, 2025, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0083965

48. Biodiversity - Coral Reefi Alliance, accessed on April 25, 2025,

49. https://coral.org/en/coral-reefis-101/why-care-about-reefis/biodiversity/
50. Attributes ofi Coral Reefi Resilience, accessed on April 25, 2025, https://reefiresilience.org/understanding-coral-reefi-resilience/
51. What is resilience? - Great Barrier Reefi Foundation, accessed on April 25, 2025, https://www.barrierreefi.org/news/explainers/what-is-resilience-great-barrier-reefi
52. Corals Tutorial: Why are coral reefis important? - NOAA's National Ocean Service, accessed on April 25, 2025, https://oceanservice.noaa.gov/education/tutorial_corals/coral07_importance.html
53. Value ofi Reefis - Reefi Resilience Network, accessed on April 25, 2025, https://reefiresilience.org/value-ofi-reefis/
54. A roadmap to integrating resilience into the practice ofi coral reefi restoration - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9545251/
55. Bleaching Susceptibility and Resistance ofi Octocorals ... - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/physiology/articles/10.3389/fiphys.2022.80419 3/fiull

56. Bleaching Susceptibility and Resistance ofi Octocorals and Anemones at the World's Southern-Most Coral Reefi - PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9161773/
57. The Octocoral Fishery in the Southeastern U.S. and Gulfi ofi Mexico - Scientific Publications Office, accessed on April 25, 2025, https://spo.nmfis.noaa.gov/sites/defiault/files/pdfi-content/mfir8032_0.pdfi
58. What makes a winner? Symbiont and host dynamics determine Caribbean octocoral resilience to bleaching - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10664981/
59. Final Report Puerto Rico Coral Reefi Monitoring Program: 2019 Survey, accessed on April 25, 2025,

60. https://www.drna.pr.gov/wp-content/uploads/2020/02/Final-Report-PRCRMP-2019_edited_.pdfi

61. Global habitat suitability ofi cold-water octocorals - PEARL - University ofi Plymouth, accessed on April 25, 2025, https://pearl.plymouth.ac.uk/cgi/viewcontent.cgi?article=1406&context=bms-rese arch
62. Water quality guidelines fior the Great Barrier Reefi - eAtlas, accessed on April 25, 2025, https://eatlas.org.au/content/water-quality-guidelines-great-barrier-reefi
63. Morphometric responses ofi two zooxanthellate octocorals along a water quality gradient in the Cuban northwestern coast - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10437867/
64. Individual and combined effect ofi organic eutrophication (DOC) and ocean warming on the ecophysiology ofi the Octocoral Pinnigorgia flava - PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9940650/
65. Spatial and Short-Term Temporal Patterns ofi Octocoral Assemblages in the West Philippine Sea - Frontiers, accessed on April 25, 2025,

66. https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2021.782977/fiull
67. Temperature and local anthropogenic pressures limit stony coral assemblage viability in southeast Florida - the NOAA Institutional Repository, accessed on April 25, 2025, https://repository.library.noaa.gov/view/noaa/62335/noaa_62335_DS1.pdfi
68. Nutritional ecology ofi temperate octocorals in a warming ocean - Frontiers, accessed on April 25, 2025,
69. https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2023.1236164/fiull
70. (PDF) Water quality as a regional driver ofi coral biodiversity and macroalgae on the Great Barrier Reefi - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/publication/44568963_Water_quality_as_a_regional

71. _driver_ofi_coral_biodiversity_and_macroalgae_on_the_Great_Barrier_Reefi
72. Influence ofi water-temperature variability on stony coral diversity in Florida Keys patch reefis, accessed on April 25, 2025, https://www.researchgate.net/publication/273911865_Influence_ofi_water-te mper ature_variability_on_stony_coral_diversity_in_Florida_Keys_patch_reefis
73. Southeast Florida Reefi Tract Water Quality Assessment - the NOAA Institutional Repository, accessed on April 25, 2025, https://repository.library.noaa.gov/view/noaa/22999/noaa_22999_DS1.pdfi
74. Coral Reefis in the Pacific | NOAA Fisheries, accessed on April 25, 2025, https://www.fisheries.noaa.gov/pacific-islands/ecosystems/coral-reefis-pa cific
75. Measuring, Interpreting, and Responding to Changes in Coral Reefis: A Challenge fior Biologists, Geologists, and Managers, accessed on April 25, 2025, https://www.nps.gov/viis/learn/nature/upload/Measuring-Interpreting-and-Res po ndingRogers-Miller2016-Accessible-2.pdfi
76. Hawai'i Reefi Restoration Monitoring Guide - The Nature Conservancy, accessed on April 25, 2025, https://www.nature.org/content/dam/tnc/nature/en/documents/Hawaii-Reefi-R est oration-Monitoring-Guide.pdfi
77. Impacts ofi a Regional, Multi-Year, Multi-Species Coral Disease Outbreak in Southeast Florida - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.20 18.0 0323/fiull
78.
www.firontiersin.org, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2 017.0 0158/fiull :~:text=While%20local%20fiactors%20can%20have,coral%20reefi%20e cosystems%20(Gattuso%20et
79. Threats to Coral Reefis | US EPA - Environmental Protection Agency, accessed on April 25, 2025, https://www.epa.gov/coral-reefis/threats-coral-reefis
80. Major Water Quality Issues Plaguing Coral Reefis Today, accessed on April 25, 2025,
81. https://coral.org/en/blog/major-water-quality-issues-plaguing-coral-reefis-today/
82. Coral Reefis | Resource Watch, accessed on April 25, 2025,
83. https://resourcewatch.org/dashboards/coral-reefis
84. Climate Change - Great Barrier Reefi Foundation, accessed on April 25, 2025, https://www.barrierreefi.org/the-reefi/threats/climate-change
85. Cold-water event ofi January 2010 results in catastrophic benthic mortality on patch reefis in the Florida Keys M. A. Colella, R, accessed on April 25, 2025,

https://ocean.floridamarine.org/fknms_wqpp/docs/cremp/reports/2012Colella%20
et%20al.%202012%20Cold%20Water%20Event%20-%20FKNMS%20Patch%20R eefis.pdfi
86. A century ofi warming on Caribbean reefis | PLOS Climate, accessed on April 25, 2025,
https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000002
87. Water Quality Protection Program - Florida Keys National Marine Sanctuary - NOAA, accessed on April 25, 2025,
https://floridakeys.noaa.gov/wqpp/
88. Florida's Coral Reefi Water Quality Data Compilation, Analysis and Decision Support, accessed on April 25, 2025,
https://floridadep.gov/rcp/coral/documents/florida%E2%80%99s-coral-reefi-wate r-quality-data-compilation-analysis-and-decision
89. National Field Manual fior the Collection ofi Water-Quality Data Chapter A2 SELECTION OF EQUIPMENT FOR WATER SAMPLING - USGS Publications
90. Warehouse, accessed on April 25, 2025,
https://pubs.usgs.gov/twri/twri9a2/Chapter2_V3-1.pdfi

91. APPENDIX E.9.1 2017 CREMP MONITORING REPORT (Part 2), accessed on April 25,

92. 2025,
93. https://ftp.nwb-oen.ca/registry/2%20MINING%20MILLING/2A/2AM%20-%20Mining/2AM-MRY1325%20BIMC/3%20TECH/1%20GENERAL%20(B)/2%20ANNUAL%20RPT/2017/180331%202AM-MRY1325%20Appendix%20E.9.1%20(Part%202)%20FI
94. NAL-IAAE.pdfi
95. 5. Relative ranking ofi reefi sites between percent CREMP coral cover, accessed on April 25, 2025,
96. https://www.researchgate.net/figure/Relative-ranking-ofi-reefi-sites-between-percent-CREMP-coral-cover-and_tbl2_254706694
97. Data Collection fior the Southeast Florida Action Network (SEAFAN, accessed on April 25, 2025,
https://floridadep.gov/sites/defiault/files/Copy%20ofi%20FINAL_Report%20to%20
FDEP%20CRCP%20Comprehensive%20Conditions%20Assessment%20Data%2 0Resources.pdfi
98. CREMP Publications, Reports, and Resources | FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/resources/
99. Water Quality Data | US EPA, accessed on April 25, 2025,
https://www.epa.gov/waterdata/water-quality-data
100. www.aoml.noaa.gov, accessed on April 25, 2025,
https://www.aoml.noaa.gov/ftp/pub/ocd/fletcher/Tools%20to%20Support%20EB
M%20ofi%20South%20Florida%20Coastal%20Resources/Percent%20Recen

t%20
Mortality%20ofi%20stony%20coral%20as%20an%20Ecolgical%20Indicator%
20o
101.
fi%20Coral%20Reefi%20Condition%20--%20Lirman%20et%20al%202014.pdfi

102. Assessing the impact ofi stony coral tissue loss disease on coral cover

103. Bonaire's Leeward side - Frontiers, accessed on April 25, 2025,
https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2024.1512371/fiull
104. Priorities fior Effective Management ofi Coral Diseases - NOAA Fisheries, accessed on April 25, 2025,
105.
https://www.fisheries.noaa.gov/s3//dam-migration/man_priorities_coral_diseases.pdfi
106. Three-dimensional model predictions ofi coral reefi dynamic evolution... - ResearchGate, accessed on April 25, 2025,
107.
https://www.researchgate.net/figure/Three-dimensional-model-predictions-ofi-coral-reefi-dynamic-evolution-with-coral_fig4_387525971
108. Coral reefi evolution notes — Coastal Processes, Environments & Systems - Tristan Salles, accessed on April 25, 2025,
https://tristansalles.github.io/Coast/reefis/reefimodel.html
109. repository.library.noaa.gov, accessed on April 25, 2025,
https://repository.library.noaa.gov/view/noaa/32881/noaa_32881_DS1.pdfi
110. Model Predicts Which Coral Reefis Will Better Adapt to Global Warming, accessed on April 25, 2025,
111.
https://cns.utexas.edu/news/research/model-predicts-which-coral-reefis-will-better-adapt-global-warming
112. Evolution and connectivity influence the persistence and recovery ofi coral reefis under climate change in the Caribbean, Southwest Pacific, and Coral Triangle - PubMed Central, accessed on April 25, 2025,
https://pmc.ncbi.nlm.nih.gov/articles/PMC8453988/

113. The unprecedented loss ofi Florida's reefi‐building corals and the ..., accessed on April 25, 2025,
https://pmc.ncbi.nlm.nih.gov/articles/PMC6851685/
114. Reefi structure ofi the Florida Reefi Tract fior the period 2005–2020 - PMC, accessed on April 25, 2025,
https://pmc.ncbi.nlm.nih.gov/articles/PMC10516784/
115. NOAA Coral Reefi Watch Methodology Page, accessed on April 25, 2025,
https://coralreefiwatch.noaa.gov/product/50km/methodology.php
116. Reefi monitoring sampling methods | AIMS, accessed on April 25, 2025,

https://www.aims.gov.au/research-topics/monitoring-and-discovery/monitoring- great-barrier-reefi/reefi-monitoring-sampling-methods
117. Annual Summary Report ofi Coral Reefi Condition 2022/23 | AIMS, accessed on April 25, 2025,
118.
https://www.aims.gov.au/monitoring-great-barrier-reefi/gbr-condition-summary-2022-23
119. Annual Summary Report ofi Coral Reefi Condition 2023/24 | AIMS, accessed on April 25, 2025,
120.
https://www.aims.gov.au/monitoring-great-barrier-reefi/gbr-condition-summary-2023-24
121. Monitoring Coral Reefis to Understand Trends in Space and Time, accessed on April 25, 2025,
https://www.coralreefi.noaa.gov/aboutcrcp/news/fieaturedstories/fieb21/monitoring

a. Economic Values fior Coral Reefi Conservation and Restoration in Florida - MDPI, accessed on April 25, 2025, https://www.mdpi.com/2076-3298/11/11/261

b. Corals Tutorial: Why are coral reefis important? - NOAA's National Ocean Service, accessed on April 25, 2025, https://oceanservice.noaa.gov/education/tutorial_corals/coral07_importance.html

c. Shallow Coral Reefi Habitat - NOAA Fisheries, accessed on April 25, 2025, https://www.fisheries.noaa.gov/national/habitat-conservation/shallow-coral-reefi- habitat

d. Threats to Coral Reefis | US EPA, accessed on April 25, 2025, https://www.epa.gov/coral-reefis/threats-coral-reefis

e. Corals and Coral Reefis - Smithsonian Ocean, accessed on April 25, 2025, https://ocean.si.edu/ocean-lifie/invertebrates/corals-and-coral-reefis

f. Stony Coral Tissue Loss Disease FAQ - FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/disease/fiaq/

g. Stony Coral Tissue Loss Disease Response | Florida Department ofi Environmental Protection, accessed on April 25, 2025, https://floridadep.gov/rcp/coral/content/stony-coral-tissue-loss-disease-respons e

h. Stony Coral Tissue Loss Disease (SCTLD), accessed on April 25, 2025, https://cdhc.noaa.gov/coral-disease/characterized-diseases/stony-coral-tissue-lo ss-disease-sctld/

i. Stony coral tissue loss disease is shifting the ecological balance ofi Caribbean

122. reefis, accessed on April 25, 2025, https://www.sciencedaily.com/releases/2024/05/240503172619.htm

a. Coral Reefi Evaluation and Monitoring Project (CREMP) - FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/

b. CREMP Overview | FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/overview/

c. Coral Reefi Monitoring | Florida Keys National Marine Sanctuary - NOAA, accessed on April 25, 2025,

123. https://floridakeys.noaa.gov/science/research-and-monitoring/coral-reefi.html

a. Coral Reefi Evaluation and Monitoring Project (CREMP) Locations | State ofi Florida Geographic Infiormation Office, accessed on April 25, 2025, https://www.floridagio.gov/datasets/myfiwc::coral-reefi-evaluation-and-monitorin g-project-cremp-locations/about

b. CREMP Methodology - FWC, accessed on April 25, 2025, https://myfiwc.com/research/habitat/coral/cremp/methodology/

c. EPA/NOAA Coral Reefi Evaluation and Monitoring Project, accessed on April 25, 2025,

124. https://ocean.floridamarine.org/fknms_wqpp/docs/cremp/reports/2002CREMPExecutiveSummary.pdfi

a. Comparison ofi Image-Acquisition Technologies Used fior Benthic Habitat Monitoring - ICRS2012, accessed on April 25, 2025, https://www.icrs2012.com/proceedings/manuscripts/ICRS2012_11B_3.pdfi

b. Coral Reefi Evaluation and Monitoring Project (CREMP), accessed on April 25, 2025, https://ocean.floridamarine.org/fknms_wqpp/coral.htm

c. CREMP Florida Keys Yearly Revisited Stony Coral Percent Coverage - Dataset - Catalog, accessed on April 25, 2025,

125.
https://catalog.data.gov/dataset/cremp-florida-keys-yearly-revisited-stony-coral-percent-coverage

a. Florida Department ofi Environmental Protection - MapDirect, accessed on April 25, 2025,

126.
https://mapdirect-fidep.opendata.arcgis.com/search?collection=Document&tags=

127. %20%20miami-dade

a. Florida Keys Coral Reefi Evaluation Monitoring Project Geodatabase Download, accessed on April 25, 2025, https://anrgeodata.vermont.gov/documents/cb844b931a2748b1a9d4c1d262cb55 8fi

b. Coral Reefi Evaluation and Monitoring Project (CREMP) Locations | State ofi Florida Geographic Inifiormation Office, accessed on April 25, 2025, https://www.floridagio.gov/datasets/myfiwc::coral-reefi-evaluation-and-monitorin g-project-cremp-locations

c. Florida Keys and Southeast Florida Coral Reefi Evaluation and Monitoring Project (CREMP/SECREMP) 295, accessed on April 25, 2025,

128. https://data.florida-seacar.org/programs/details/295

a. Florida's Coral Reefi 2023-2024 Post-Bleaching Assessment Quick Look Report, accessed on April 25, 2025,

129.
https://ocean.floridamarine.org/FRRP/TrainingDocs/UPDATED%202024%20Post-Bl eaching%20Quick%20Look%20Report.pdfi

a. Coral Reefi Evaluation and Monitoring Project Florida Keys 2018 - IPT, accessed on April 25, 2025,

130.
https://ipt-obis.gbifi.us/resource?r=coralreefievaluationandmonitoringproject-2018

a. Coral Reefi Evaluation and Monitoring Project Florida Keys 2001 - IPT, accessed on April 25, 2025,

131.
https://ipt-obis.gbifi.us/resource?r=coralreefievaluationandmonitoringproject-2001

a. Florida Reefi Tract Temperature Monitoring - CREMP Sites - Overview, accessed on April 25, 2025, https://www.arcgis.com/home/item.html?id=ec186eecb25b48a99830fi2b20741e9 47

b. ocean.floridamarine.org, accessed on April 25, 2025, https://ocean.floridamarine.org/fknms_wqpp/docs/cremp/reports/2004CREMPEx ecutiveSummary.pdfi

c. Global Coral Reefi Monitoring Network: GCRMN, accessed on April 25, 2025, https://gcrmn.net/

d. Global Coral Reefi Monitoring Network | Department ofi Economic and Social Affairs, accessed on April 25, 2025,

132. https://sdgs.un.org/partnerships/global-coral-reefi-monitoring-network

a. The Global Coral Reefi Monitoring Network- Charting a Course Toward Data Interoperability, accessed on April 25, 2025, https://www.coralreefi.noaa.gov/aboutcrcp/news/fieaturedstories/may22/gcrmn/w elcome.html

b. 2020 Report – GCRMN - Global Coral Reefi Monitoring Network, accessed on April 25, 2025, https://gcrmn.net/2020-report/

c. Status ofi Coral Reefis ofi the World 2020 | UNEP - UN Environment Programme, accessed on April 25, 2025,

133. https://www.unep.org/resources/status-coral-reefis-world-2020

a. Coral Bleaching On-Site Monitoring Tools - Coral Reefi Alliance, accessed on April 25, 2025, https://coral.org/en/coral-bleaching/on-site-monitoring-tools/

b. Reefi Check Foundation | Supporting the World's Reefis, accessed on April 25, 2025, https://www.reeficheck.org/

c. NOAA Coral Reefi Watch Homepage and Near Real-Time Products Portal, accessed on April 25, 2025, https://coralreefiwatch.noaa.gov/

d. World's First Satellite-Based Coral Reefi Monitoring System Deploys Globally, Paving the Way fior Innovation Driven Conservation, accessed on April 25, 2025, https://allencoralatlas.org/blog/worlds-first-satellite-based-coral-reefi-monitoring

134. -system-deploys-globally-paving-the-way-fior-innovation-driven-conservation/

a. NOAA Coral Reefi Watch | Adaptation Clearinghouse, accessed on April 25, 2025, https://www.adaptationclearinghouse.org/resources/noaa-coral-reefi-watch.html

b. NOAA Coral Reefi Watch 5km Methodology Page, accessed on April 25, 2025, https://coralreefiwatch.noaa.gov/product/5km/methodology.php

c. Allen Coral Atlas, accessed on April 25, 2025, https://allencoralatlas.org/

d. NCRMP Data Visualization Tool - Overview, accessed on April 25, 2025,

135. https://www.arcgis.com/home/item.html?id=fidd16e56c8964bee82679e0b86ea87d8

a. Hawaii Coral Reefi Assessment and Monitoring Program (CRAMP) benthic data and still images firom 2017-05-22 to 2017-08-27 on Oahu and Kauai (NCEI Accession 0222168), accessed on April 25, 2025, https://catalog.data.gov/dataset/hawaii-coral-reefi-assessment-and-monitoring-p rogram-cramp-benthic-data-and-still-images-firom-202

b. Comparison ofi Standard Caribbean Coral Reefi Monitoring Protocols and Underwater Digital Photogrammetry to Characterize Hard Coral Species Composition, Abundance and Cover - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2021.7 22569/fiull

c. Scaling up Coral Reefi Impact With Open Data and PostgreSQL - EDB, accessed on April 25, 2025,

136. https://www.enterprisedb.com/blog/scaling-coral-reefi-impact-open-data-and-postgresql

a. MERMAID, accessed on April 25, 2025, https://datamermaid.org/

b. MERMAID - WCS.org, accessed on April 25, 2025, https://www.wcs.org/our-work/species/coral/mermaid

c. Visualization and quantification ofi coral reefi soundscapes using CoralSoundExplorer software | PLOS Computational Biology, accessed on April 25, 2025,

137.
https://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1012050

a. Coral Reefis Health Monitoring | EarthToolsMaker, accessed on April 25, 2025, https://www.earthtoolsmaker.org/projects/coral_reefi_health_monitoring/

b. U.S. Coral Reefis | US EPA, accessed on April 25, 2025, https://www.epa.gov/coral-reefis/us-coral-reefis

c. Biodiversity - Coral Reefi Alliance, accessed on April 25, 2025, https://coral.org/en/coral-reefis-101/why-care-about-reefis/biodiversity/

d. Basic Infiormation about Coral Reefis | US EPA, accessed on April 25, 2025, https://www.epa.gov/coral-reefis/basic-infiormation-about-coral-reefis

e. Visual Feature | Status ofi Coral Reefis ofi the World - UNEP, accessed on April 25, 2025, https://www.unep.org/interactive/status-world-coral-reefis/

f. Stony coral tissue loss disease indirectly alters reefi communities - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11068009/

g. Re-evaluating the health ofi coral reefi communities: baselines and evidence fior human impacts across the central Pacific - Journals, accessed on April 25, 2025, https://royalsocietypublishing.org/doi/10.1098/rspb.2015.1985

h. Species Richness and Community Structure on a High Latitude Reefi: Implications fior Conservation and Management - MDPI, accessed on April 25, 2025, https://www.mdpi.com/1424-2818/3/3/329

i. Species richness accelerates marine ecosystem restoration in the Coral Triangle - PNAS, accessed on April 25, 2025, https://www.pnas.org/doi/10.1073/pnas.1707962114

j. Species identity and composition shape productivity ofi stony corals - bioRxiv,

138. accessed on April 25, 2025,
https://www.biorxiv.org/content/10.1101/2024.06.20.599878v1.fiull-text

a. Species Richness and Abundance ofi Reefi-Building Corals in the Indo-West Pacific: The Local–Regional Relation Revisited - Frontiers, accessed on April 25, 2025,

139.
https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2020.00487/fiull

a. Temperature and local anthropogenic pressures limit stony coral assemblage viability in southeast Florida - the NOAA Institutional Repository, accessed on April 25, 2025, https://repository.library.noaa.gov/view/noaa/62335/noaa_62335_DS1.pdfi

b. The Effects ofi Coral Diversity on Prevalence and Impacts ofi Stony Coral Tissue Loss Disease in Saint Thomas - the NOAA Institutional Repository, accessed on April 25, 2025, https://repository.library.noaa.gov/view/noaa/62361/noaa_62361_DS1.pdfi

c. Caribbean octocoral communities: finding the fiorest fior the trees? - bioRxiv, accessed on April 25, 2025, https://www.biorxiv.org/content/10.1101/2025.01.05.631368v1

d. Caribbean octocoral communities: finding the fiorest fior the trees? Howard R Lasker1, Lorenzo Bramanti2, Peter J. Edmunds3, John - bioRxiv, accessed on April 25, 2025, https://www.biorxiv.org/content/10.1101/2025.01.05.631368v1.fiull.pdfi

e. The Octocoral Trait Database: a global database ofi trait infiormation fior octocoral species - PMC - PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11735844/

f. Know Thy Anemone: A Review ofi Threats to Octocorals and Anemones and Opportunities fior Their Restoration - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2020. 00590/fiull

g. Diversity and Evolution ofi Octocoral Animal Forests at Both Sides ofi Tropical America | Request PDF - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/publication/318804410_Diversity_and_Evolution_ofi

140. _Octocoral_Animal_Forests_at_Both_Sides_ofi_Tropical_America

a. The rise ofi octocoral fiorests on Caribbean reefis - WHOI GFD, accessed on April 25, 2025,

141.
https://gfid.whoi.edu/wp-content/uploads/sites/14/2023/02/Laskeretal2020riseofioctocorals.pdfi

a. Portfolio effects and fiunctional redundancy contribute to the maintenance ofi octocoral fiorests on Caribbean reefis - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9061744/

b. What makes a winner? Symbiont and host dynamics determine Caribbean octocoral resilience to bleaching - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC10664981/

c. Quantifiying impacts ofi stony coral tissue loss disease on corals in Southeast Florida through surveys and 3D photogrammetry - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC8232449/

d. Bioassessment Tools fior Stony Corals: Field Testing ofi Monitoring Protocols in the US Virgin Islands (St. Croix) - Environmental Protection Agency (EPA), accessed on April 25, 2025,

142. https://www.epa.gov/sites/defiault/files/2019-03/documents/field-testing-vi-stcroix.pdfi

a. Mean (± SE) annual live tissue area (LTA) fior all stony coral species... - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/figure/Mean-SE-annual-live-tissue-area-LTA-fior-all

143. -stony-coral-species-and-sites-combined_fig2_362964331

a. Black Band Disease - Coral Disease & Health Consortium - NOAA, accessed on April 25, 2025,

144. https://cdhc.noaa.gov/coral-disease/characterized-diseases/black-band-disease/

a. What are the major threats to corals? - Diseases - NOAA's National Ocean Service, accessed on April 25, 2025, https://oceanservice.noaa.gov/education/tutorial_corals/coral10_disease.html

b. Why is Coral Health Important? - UH Hilo, accessed on April 25, 2025, https://hilo.hawaii.edu/coralhealth/coral-health.php

c. Sulfide, microcystin, and the etiology ofi black band disease - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC3518071/

d. Ecological and molecular characterization ofi a coral black band disease outbreak in the Red Sea during a bleaching event - PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC6046197/

e. Coral disease conditions scored during the Coral Reefi Monitoring Project Station Species Inventories - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/figure/Coral-disease-conditions-scored-during-th e-Coral-Reefi-Monitoring-Project-Station-Species_tbl1_226929811

f. Coral Disease - Florida Department ofi Environmental Protection, accessed on April 25, 2025, https://floridadep.gov/sites/defiault/files/coral-disease2.pdfi

g. Priorities fior Effective Management ofi Coral Diseases - NOAA Fisheries, accessed on April 25, 2025,

145. https://www.fisheries.noaa.gov/s3//dam-migration/man_priorities_coral_diseases.pdfi

a. Coral Disease Handbook - University ofi Guam, accessed on April 25, 2025, https://www.uog.edu/_resources/files/ml/raymundolab/books/CRTR_DiseaseHand book_Final.pdfi

b. Reefi monitoring sampling methods | AIMS - The Australian Institute ofi Marine Science, accessed on April 25, 2025,

146. https://www.aims.gov.au/research-topics/monitoring-and-discovery/monitoring-great-barrier-reefi/reefi-monitoring-sampling-methods

a. Comparison ofi methods used to estimate coral cover in the Hawaiian Islands - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC4435506/

b. Which statistical methods can be applied fior analysis ofi time-series data on percent cover ofi benthic fiorms in a coral reefi ecosystem? | ResearchGate, accessed on April 25, 2025,

147. https://www.researchgate.net/post/Which_statistical_methods_can_be_applied_fior_analysis_ofi_time-series_data_on_percent_cover_ofi_benthic_fiorms_in_a_coral

148. _reefi_ecosystem

a. Assessing the impact ofi stony coral tissue loss disease on coral cover on Bonaire's Leeward side - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2024.1 512371/fiull

b. Rapid Assessment ofi Stony Coral Richness and Condition on Saba Bank, Netherlands Antilles | PLOS One, accessed on April 25, 2025, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0010749

c. Spatial and Temporal Trends ofi Southeastern Florida's Octocoral Comunity - NSUWorks, accessed on April 25, 2025, https://nsuworks.nova.edu/cgi/viewcontent.cgi?article=1532&context=occ_stuetd

d. Assessing Coral Reefi Changes through Supervised Classification and its Correlation with SST and Chlorophyll-A: A Remote Sensing, accessed on April 25, 2025,

149. https://www.fig.net/resources/proceedings/fig_proceedings/nepal/papers/ts03b/TS03B_upadhyay_parajuli_et_al_12876.pdfi

a. Correlation between Coral Reefi Condition and the Diversity and Abundance ofi Fishes and Sea Urchins on an East Afirican Coral Reefi - MDPI, accessed on April 25, 2025, https://www.mdpi.com/2673-1924/3/1/1

b. Coral Reefi Monitoring, Reefi Assessment Technologies, and Ecosystem-Based Management - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2019.0 0580/fiull

c. The Vital Link: Why Water Quality Matters fior Coral Reefis, accessed on April 25, 2025,

150. https://coral.org/en/blog/the-vital-link-why-water-quality-matters-fior-coral-reefis

151.

/

a. Toward a New Era ofi Coral Reefi Monitoring | Environmental Science & Technology, accessed on April 25, 2025, https://pubs.acs.org/doi/10.1021/acs.est.2c05369

b. Chapter 2: Monitoring Coral Reefi Health, accessed on April 25, 2025, https://www.coris.noaa.gov/activities/reportcongress2008/chapter2_monitoring.p dfi

c. Innovative Techniques Provide New Means to Monitor Coral Reefi Health, accessed on April 25, 2025,

152. https://www.whoi.edu/press-room/news-release/innovative-techniques-provide-new-means-to-monitor-coral-reefi-health/

a. Seasonal Prediction ofi Thermal Stress Accumulation fior Coral Bleaching in the Tropical Oceans, accessed on April 25, 2025, https://journals.ametsoc.org/view/journals/mwre/139/2/2010mwr3526.1.pdfi

b. The 27–year decline ofi coral cover on the Great Barrier Reefi and its causes | PNAS, accessed on April 25, 2025, https://www.pnas.org/doi/10.1073/pnas.1208909109

c. Forecasting intensifiying disturbance effects on coral reefis - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/publication/339619536_Forecasting_intensifiying_di sturbance_effects_on_coral_reefis

d. Coral Reefis | National Marine Ecosystem Status - NOAA, accessed on April 25, 2025, https://ecowatch.noaa.gov/thematic/coral-reefis

e. Operational Ecofiorecasting fior Coral Reefis Using Artificial Intelligence and Integrated Near Real-Time Environmental Data - Ingenta Connect, accessed on April 25, 2025, https://www.ingentaconnect.com/content/umrsmas/bullmar/2023/00000099/00 000003/art00010?crawler=true&mimetype=application/pdfi

f. Remote Sensing ofi Coral Reefis fior Monitoring and Management: A Review - MDPI, accessed on April 25, 2025, https://www.mdpi.com/2072-4292/8/2/118

g. STATUS AND TRENDS OF CORAL REEFS OF THE PACIFIC, accessed on April 25,

153. 2025,

154. https://gcrmn.net/wp-content/uploads/2022/06/Status-and-Trends-ofi-Coral-Reefis-ofi-the-Pacific-2018.pdfi

a. Monitoring and Interventions - AGRRA, accessed on April 25, 2025, https://www.agrra.org/experimental-interventions/

b. Long-Term Monitoring ofi Coral Reefis ofi the Main Hawaiian Islands Final Report, accessed on April 25, 2025, https://dlnr.hawaii.gov/dar/files/2014/04/NOAA_2013_WHi_-Mon_-Rep.pdf i

c. Multi-Factor Coral Disease Forecast - NOAA Coral Reefi Watch, accessed on April 25, 2025, https://coralreefiwatch.noaa.gov/product/disease_multifiactor/

d. Optimization ofi thermal stress thresholds on regional coral bleaching monitoring by satellite measurements ofi sea surfiace temperature - Frontiers, accessed on April 25, 2025,

155. https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2024.1 438087/fiull

a. Lag Effects in the Impacts ofi Mass Coral Bleaching on Coral Reefi Fish, Fisheries, and Ecosystems | Request PDF - ResearchGate, accessed on April 25, 2025,

156. https://www.researchgate.net/publication/5960661_Lag_Effects_in_the_Impacts_ofi_Mass_Coral_Bleaching_on_Coral_Reefi_Fish_Fisheries_and_Ecosystems

a. Warming Alters the Relationship Between Benthic Cover and Herbivores on Hawaiian Reefis, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2022.7 87314/fiull

b. The impact ofi rising temperatures on the prevalence ofi coral diseases and its predictability - EcoEvoRxiv, accessed on April 25, 2025, https://ecoevorxiv.org/repository/object/4833/download/9603/

c. Global patterns and impacts ofi El Niño events on coral reefis: A meta-analysis - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC5798774/

d. Climate change as experienced by corals | Coral Guardian, accessed on April

157. 25, 2025,

158.
https://www.coralguardian.org/en/coral-reefis-experience-ofi-climate-change/

a. Volatility in coral cover erodes niche structure, but not diversity, in reefi fish assemblages, accessed on April 25, 2025, https://www.science.org/doi/10.1126/sciadv.abm6858

b. Elevated Sea Surfiace Temperatures Correlate with Caribbean Coral Reefi Bleaching, accessed on April 25, 2025, https://globalcoral.org/_oldgcra/elevated_sea_surfiace_temperature.htm

c. Thermal Stress and Coral Cover as Drivers ofi Coral Disease Outbreaks - PMC

i. PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC1865563/

d. Rising sea surfiace temperatures driving the loss ofi 14 percent ofi corals since 2009 - UNEP, accessed on April 25, 2025,

159.
https://www.unep.org/news-and-stories/press-release/rising-sea-surfiace-temperatures-driving-loss-14-percent-corals-2009

a. Remote Sensing Reveals Multidecadal Trends in Coral Cover at Heron Reefi, Australia, accessed on April 25, 2025, https://www.mdpi.com/2072-4292/17/7/1286

b. A Multimarker Approach to Identifiy Microbial Bioindicators fior Coral Reefi Health Monitoring—Case Study in La Réunion Island - PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11772467/

c. High summer temperatures amplifiy fiunctional differences between coral‐ and algae‐dominated reefi communities - PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7900985/

d. Permanent 'phase shifts' or reversible declines in coral cover?: Lack ofi recovery ofi two coral reefis in St. John, US Virgin Islands - Inter-Research Science Publisher, accessed on April 25, 2025,

160. https://www.int-res.com/articles/meps2006/306/m306p103.pdfi

a. The Dynamics ofi Coral-Algal Interactions in Space and Time on the Southern Great Barrier Reefi - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2018.0 0181/fiull

b. Responses ofi coral reefis and reefi organisms to sedimentation, accessed on April 25, 2025, https://www.coralreefi.gov/assets/mitigation/responsescoralreefis_organismssedi mentation.pdfi

c. Coral Reefis and Climate Change, accessed on April 25, 2025, https://www.ocean-climate.org/wp-content/uploads/2017/03/coral-reefis-climate- change_ScientificNotes_Oct2016_BD_ppp-6.pdfi

d. Spatial distribution ofi benthic microalgae on coral reefis determined by remote sensing, accessed on April 25, 2025, https://www.researchgate.net/publication/43441825_Spatial_distribution_ofi_bent hic_microalgae_on_coral_reefis_determined_by_remote_sensing

e. Variable Growth Across Species and Lifie Stages in Caribbean Reefi Octocorals

i. Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2020.

161. 00483/pdfi

a. Lasker et al. Octocoral fiorests on Caribbean reefis Resilience ofi Octocoral Forests to Catastrophic Storms, accessed on April 25, 2025, https://par.nsfi.gov/servlets/purl/10142086

b. Southeast Florida Coral Reefi Evaluation and Monitoring Project, accessed on April 25, 2025, https://floridadep.gov/sites/defiault/files/Yr%2016%20SECREMP_Final%20Compre hensive%20Report_FINAL_revised.pdfi

c. Southeast Florida Coral Reefi Evaluation and Monitoring Project, accessed on April 25, 2025, https://floridadep.gov/sites/defiault/files/Yr%2018%20SECREMP_Comprehensive% 20Report_Final.pdfi

d. Coral Reefi Monitoring Manual fior the Caribbean and Western Atlantic, accessed on April 25, 2025,

162. https://reefiresilience.org/wp-content/uploads/Coral_Reefi_Monitoring_Manual_Ca rib-WesternAtlantic.pdfi

a. Coral species composition drives key ecosystem fiunction on coral reefis - PubMed Central, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7062023/

b. Species-specific responses to climate change and community composition determine fiuture calcification rates ofi Florida Keys reefi - the NOAA Institutional Repository, accessed on April 25, 2025, https://repository.library.noaa.gov/view/noaa/20166/noaa_20166_DS1.pdfi

c. Biodiversity ofi coral reefi cryptobiota shuffles but does not decline under the combined stressors ofi ocean warming and acidification | PNAS, accessed on April 25, 2025, https://www.pnas.org/doi/10.1073/pnas.2103275118

d. Early Warning Systems 1 Module 5 - NOAA Coral Reefi Watch, accessed on April 25, 2025, https://coralreefiwatch.noaa.gov/satellite/education/workshop/docs/workbook_mo dule2_early_warning.pdfi

e. Predictive Analytics fior Coral Bleaching Early Warning Systems → Scenario, accessed on April 25, 2025,

163. https://prism.sustainability-directory.com/scenario/predictive-analytics-fior-coral-bleaching-early-warning-systems/

a. Meteorological Monitoring - Coral Reefi Research Foundation, accessed on April 25, 2025, https://coralreefipalau.org/research/oceanographyweather/meteorological-monito ring/

b. Reefi Health Index, accessed on April 25, 2025, https://www.healthyreefis.org/en/healthy-reefis-data/indicators/reefi-health-index

c. Benthos indicators fior coral reefi health - agrra, accessed on April 25, 2025, https://www.agrra.org/coral-reefi-monitoring/benthos-indicator/

d. Mapped coral mortality and refiugia in an archipelago-scale marine heat wave

i. PMC, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9171643/

e. Initial Great Barrier Reefi monitoring results show coral mortality in north due to bleaching and cyclones - The Australian Institute ofi Marine Science, accessed on April 25, 2025,

164.
https://www.aims.gov.au/inforrmation-centre/news-and-stories/initial-great-barrie r-reefi-monitoring-results-show-coral-mortality-north-due-bleaching-and-cyclo nes

a. Unprecedented Coral Mortality on Southwestern Atlantic Coral Reefis Following Major Thermal Stress - Frontiers, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars .2022.7 25778/fiull

b. A Glimmer ofi Good News firom the Mesoamerican Reefi as reefi health improved fior the first time in five years, although the overall grade remains “poor” – GCRMN - Global Coral Reefi Monitoring Network, accessed on April 25, 2025, https://gcrmn.net/2024/11/08/mesoamerican-report-card-2024/

c. Long-Term Monitoring Program - Annual Summary Report ofi Coral Reefi Condition 2020/21, accessed on April 25, 2025,

165.
https://www.aims.gov.au/reefi-monitoring/gbr-condition-summary-2020-2021

a. Restoring Coral Reefis | NOAA Fisheries, accessed on April 25, 2025, https://www.fisheries.noaa.gov/national/habitat-conservation/restoring-cor al-reefi s

b. Long-Term Monitoring ofi Coral Reefis ofi the Main Hawaiian Islands Final Report - Malama Maunalua, accessed on April 25, 2025, https://www.malamamaunalua.org/wp-content/uploads/DLNR-DAR-2010.p dfi

c. Coral reefi ecosystems | National Oceanic and Atmospheric Administration, accessed on April 25, 2025,

166.
https://www.noaa.gov/education/resource-collections/marine-lifie/coral-reefi-ecos ystems

a. Healthy Reefis - CCMI - Central Caribbean Marine Institute, accessed on April 25, 2025, https://reefiresearch.org/get-involved/healthy-reefi/

b. Coral Reefi Surveillance with Machine Learning: A Review ofi Datasets, Techniques, and Challenges - MDPI, accessed on April 25, 2025, https://www.mdpi.com/2079-9292/13/24/5027

c. Anomaly detection in fieature space fior detecting changes in phytoplankton populations, accessed on April 25, 2025, https://www.firontiersin.org/journals/marine-science/articles/10.3389/fimars.2023.1 283265/fiull

d. Anomaly Detection Techniques: How to Uncover Risks, Identifiy Patterns, and Strengthen Data Integrity - MindBridge, accessed on April 25, 2025, https://www.mindbridge.ai/blog/anomaly-detection-techniques-how-to-uncover

167. -risks-identifiy-patterns-and-strengthen-data-integrity/

a. Advanced Data Anomaly Detection: Using the Power ofi Machine Learning - Acceldata, accessed on April 25, 2025,

168. https://www.acceldata.io/blog/advanced-data-anomaly-detection-with-machine-learning-a-step-by-step-guide

a. Survey: Anomaly Detection Methods - Computer Science and Engineering,

169. accessed on April 25, 2025, https://www.cs.ucr.edu/~egujr001/ucr/madlab/publication/EG_2023_Anomaly_Det ection_Methods.pdfi

a. Real-Time Anomaly Detection: Use Cases and Code Examples - Tinybird, accessed on April 25, 2025,

170. https://www.tinybird.co/blog-posts/real-time-anomaly-detection

a. Coral Reefi Temperature Anomaly Database | National Centers fior Environmental Infiormation (NCEI), accessed on April 25, 2025, https://www.ncei.noaa.gov/products/coral-reefi-temperature-anomaly-database

b. NOAA Coral Reefi Watch Methodology Page, accessed on April 25, 2025, https://coralreefiwatch.noaa.gov/product/50km/methodology.php

c. Spatial distribution ofi coral reefi monitoring sampling effort on... - ResearchGate, accessed on April 25, 2025, https://www.researchgate.net/figure/Spatial-distribution-ofi-coral-reefi-monitorin g-sampling-effort-on-Australias-Great_fig1_339858339

d. Analyzing the Relationship Between Ocean Temperature Anomalies and Coral Disease Outbreaks at Broad Spatial Scales - John Bruno, accessed on April 25, 2025,

171. https://johnfbruno.web.unc.edu/wp-content/uploads/sites/1927/2011/11/Selig-et-al

172. -2006.pdfi

a. Stress on the Great Barrier Reefi - NASA Earth Observatory, accessed on April 25, 2025,

173. https://earthobservatory.nasa.gov/images/89827/stress-on-the-great-barrier-reefi

a. Resilient Coral | Stanfiord Woods Institute fior the Environment, accessed on April 25, 2025, https://woods.stanfiord.edu/news/resilient-coral

b. A generalized machine learning model fior long-term coral reefi monitoring in the Red Sea, accessed on April 25, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC11458965/

c. Monitoring shallow coral reefi exposure to environmental stressors using satellite earth observation - UCL Discovery, accessed on April 25, 2025, https://discovery.ucl.ac.uk/id/eprint/10162325/1/Remote%20Sens%20Ecol%20Con serv%20-%202022%20-%20Williamson%20-%20Monitoring%20shallow%20cora l%20reefi%20exposure%20to%20environmental%20stressors%20using.pdfi

174. -coral-reefis.html

175. Coral Reefi Monitoring | Florida Keys National Marine Sanctuary, accessed on April 25, 2025,

176. https://floridakeys.noaa.gov/science/research-and-monitoring/coral-reefi.html

177. National Coral Reefi Monitoring Program: Water temperature data firom subsurfiace temperature recorders (STRs) deployed at coral reefi sites in the Hawaiian Archipelago - NOAA, accessed on April 25, 2025, https://accession.nodc.noaa.gov/NCRMP-STR-HI

178. Visual Feature | Status ofi Coral Reefis ofi the World - UNEP, accessed on April 25, 2025, https://www.unep.org/interactive/status-world-coral-reefis/

179. Report finds a 14 per cent coral loss since 2009 - Oceanographic Magazine, accessed on April 25, 2025, https://oceanographicmagazine.com/news/corals-global-warming/

180. Status ofi Coral Reefis ofi the World: 2020, accessed on April 25, 2025, https://gcrmn.net/wp-content/uploads/2022/05/Chapter-2.-Status-ofi-Coral-Reefi s-ofi-the-World.pdfi

181.

Status-ofi-Coral-Reefis-ofi-the-World-2020-Summary-fior-Policymakers.pdfi,

182. accessed on April 25, 2025,

183. https://gcrmn.net/wp-content/uploads/2022/05/Status-ofi-Coral-Reefis-ofi-the-World-2020-Summary-fior-Policymakers.pdfi

184. Science & Methods - Allen Coral Atlas, accessed on April 25, 2025, https://allencoralatlas.org/methods/