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Original Research Paper

Long Term Monitoring of Coral Reef Fish Populations Under Increasing Ocean Temperature and Acidification Stress

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Key Words

Coral reef fish diversity, Ocean warming, Ocean acidification, NOAA NCRMP, Shannon Diversity index, Climate change monitoring.

Abstract

Coral reefs are especially sensitive to ocean warming and acidification caused by climate change and can have a major impact on reef-associated fish species and reef stability. This study analyzes the diversity of coral reef fishes over time using data from the National Coral Reef Monitoring Program (NCRMP) of NOAA from the year 2014 to 2024 from the Hawaiian Archipelago. The impacts of environmental factors such as sea surface temperature, ocean pH, and coral cover were evaluated on fish population structure. Shannon Diversity Index as the main statistical method to quantify the changes in biodiversity between monitoring years. The mean sea surface temperature (MST) ranged from 26.8°C in 2014 to 29.1°C in 2024, with a steady increase over the years, whereas the mean pH decreased from 8.12 to 7.95 over the years. During the same time frame, there was significant loss of coral cover, from 62% to 36%. The Shannon Diversity Index was then found to have decreased from 3.45 to 2.51, representing a loss of some 27.2% of biodiversity. The results indicate that the diversity of coral reef fishes is negatively correlated with environmental stress. Fish functional groups were further simplified, with habitat specialist fishes being more affected than generalist fishes under climate stress. The rising temperature and acidification of the oceans are important factors in the decline of coral reef fish. The continued monitoring and adaptive conservation strategies will be critical to ensure that reef biodiversity will persist into the future under different climate change scenarios.

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Introduction

Although coral reefs cover only one percent of the ocean floor, contain almost one-quarter of all marine fish species and are the most biologically diverse and productive marine ecosystems. Play a vital role in the provision of ecosystem services such as biodiversity conservation, coastal protection, fisheries productivity, and nutrient cycling. Recently, however, coral reef habitat is under threats from anthropogenic climate change, including ocean warming and ocean acidification, which are impacting ecological processes in the ocean at an unprecedented rate (Wang et al., 2024).

One of the most important stressors to coral reef resilience is ocean warming. Higher SSTs induce physiological stress in organisms living in association with corals, and their impacts have been documented on behavioral adaptation, learning, and memory in coral reef fishes, which ultimately can impact their survival and reproductive success when exposed to heat for extended periods of time (Silveira et al., 2023). The effects of warming are variable between species and can make interspecific competition stronger and alter the balance in reef communities (Mitchell et al., 2023). The effects of these shifts are significant for the stability of reef fish assemblages, particularly in reef systems that are already under stress due to recurrent bleaching events.

Absorbed carbon dioxide in the atmosphere is increasing the amount of carbon dioxide in the ocean, which further compromises the integrity of reef ecosystems by depleting levels of carbonate ions required for the building of coral skeletons and for coral calcification. Experimental studies conducted recently suggest that the acidified condition affects the neural responses of fishes and causes a transcriptional change towards acclimation stress but varies widely among taxa (Suresh et al., 2023). There are also effects of acidification that reduce the ability of the coral holobiont to recover from thermal perturbations and may decrease resistance to additional stresses (Dobson et al., 2024).

Thermal stress and acidification can have synergistic ecological impacts. Across longer time frames, some experimental studies indicate that even those species that have been stressed repeatedly over time will not stay at their optimal physiological state under projected future conditions (Roper et al., 2023). These results suggest that the natural acclimatization processes might not be enough to mitigate the damage to the reefs from climate change. This results in a decrease in coral structural complexity, which decreases the suitability of the coral habitat for reef-associated fishes and causes biodiversity loss (Thirukanthan et al., 2023).

The complexity of coral reef habitat is of critical importance to coral reef fishes for protection, feeding, reproductive success, and juvenile recruitment. Habitat specialist species are vulnerable when degradation occurs and can even be driven to extinction, while ecological generalists can survive or even thrive in modified habitats (Aghazadeh et al., 2016). The change in community structure to fewer species can affect the trophic dynamics and decrease the functioning of the ecosystem.

Long-term monitoring of the ecology can give important insights into the response of reef fish to the cumulative effects of environmental stressors. The combination of fish population surveys with ecological monitoring systems will help to identify subtle changes in species abundance, behavioral adaptation, and ecosystem resilience over longer time scales (Tandi, 2025). This monitoring is also becoming more relevant to detect early warning signs of ecological failure and guide adaptive conservation action.

There is a new hope for the restoration of corals through recent advances in coral conservation biotechnology, such as assisted evolution and interventions for reef rehabilitation that enhance coral climate stress tolerance (Cecchini et al., 2024). But proper management needs to rely on the proper knowledge of the response of fishes to environmental changes, because fish of the reefs play an important role in the ecosystem recovery through their herbivory, nutrient cycling, and trophic regulation.

The larger-scale distribution of coastal biodiversity is also being affected by climate-driven changes, which include changes to the distribution of species, food web interactions, and the stability of the ecosystems providing services (Ali et al., 2024). While there are several stresses that affect marine ecosystems, such as the effects of heavy metals and localized pollution pressures (Mustapha et al., 2017), the global large-scale decline of coral reefs is mainly attributable to thermal and acidification stresses resulting from climate change.

Although these threats are well recognized, there are few long-term studies that relate coral reef fish population dynamics with ocean warming and acidification. Previous studies have tended to concern short-term experimental observations rather than an analysis on the scale of the ecosystem over time. The enormous amount of data available from programs like the NOAA National Coral Reef Monitoring Program provides an unprecedented opportunity to assess changes in fish abundance, diversity of species, and their functional diversity in response to changing ocean conditions over 10+ years.

Thus, this study explores the long-term trends of coral reef fish populations in the context of the rising threats of ocean warming and acidification, based on the monitoring data from NOAA's NCRMP. This study is designed to determine the temporal trends in fish community structure, identify environmental factors that may affect population declines, and understand the implications of these ecological changes for reef conservation in the future.

Research Gap

While there are many studies on the impact of ocean warming and acidification on coral physiology and fish behavior, there are fewer studies that have focused on the long-term (population-level) impacts of combined stressors on coral reef fishes. The majority of studies available are experimental or local and have a lack of data with decadal-scale monitoring that are able to represent the temporal trends in abundance, diversity, and functional composition of species. Additionally, there is a lack of integration between environmental variables and fish community responses at a large scale, based on ecological data. This is a gap that hinders the ability to predict accurately how climate change will affect reef ecosystem change and reiterates the importance of multiple long-term analyses that rely on a standard monitoring framework like NOAA NCRMP.

Objectives

- To determine trends in coral reef fish abundance and species diversity from NOAA NCRMP monitoring data over time.
- To assess the link between warming, stress of ocean acidification, and reef fish population structure change.
- To determine fish functional groups that are vulnerable and resilient to changes in the reef ecosystem and support predictions of future response to climate change scenarios.

Paper Organization

There are 4 parts to the paper. Section 1 provides a background of the research, research objectives, and significance of the research study. The materials, NOAA NCRMP dataset, and methodology used for statistical analysis are described in Section 2. In Section 3, the results and discussion are presented in relation to the changes in coral reef fish diversity over time in the presence of environmental stress. Major findings, implications, and future research directions are summarized in section 4, the last section of the study.

Materials and Methods

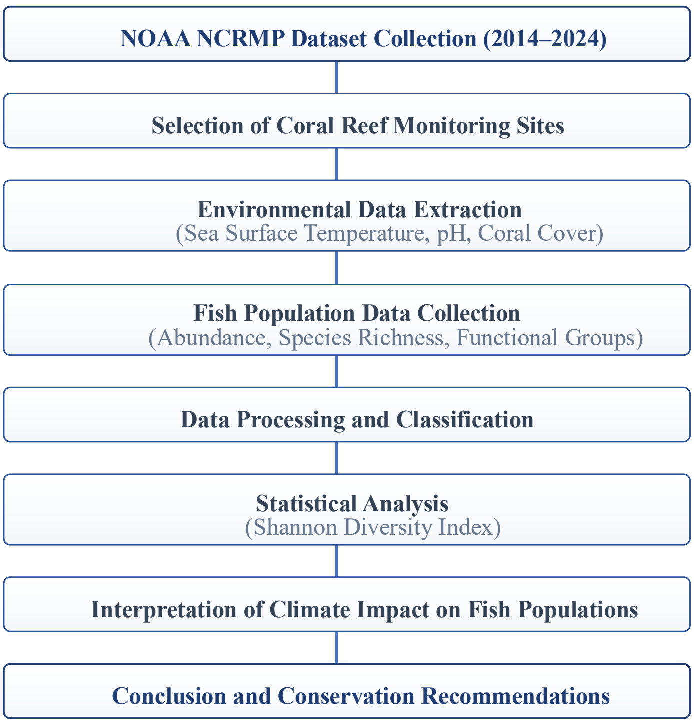

Figure 1. Methodological Framework for Long-Term Monitoring of Coral Reef Fish Populations

The methodology applied in this study is shown in figure 1 as a general methodology. The process starts with data collection and site selection by NOAA NCRMP and then extraction of the environmental variables sea surface temperature, pH, and coral cover. The data for fish populations, such as abundance, species richness, and functional groups, were then processed and classified. Ocean warming and acidification impacts on coral reef fish populations were statistically evaluated by diversity assessment, regression and the advice for conservation was provided.

Study Area

Data from the NOAA National Coral Reef Monitoring Program (NCRMP) were used to conduct the study on selected reef sites in the Hawaiian Archipelago for the years 2014-2024. These sites are ecologically relevant coral reef areas, where subjected to different levels of stress by warming and acidification of the ocean.

Data Source and Collection

Standardized stationary point count surveys were used to obtain fish population and habitat information from the NCRMP database. The information in the dataset encompassed fish abundance, species richness, fish biomass, coral cover, reef rugosity, depth, and site coordinates that were obtained from repeated annual monitoring.

Environmental Variables

Various oceanographic variables such as sea surface temperature anomalies and ocean acidification measures from NOAA ocean monitoring data were used to evaluate the environment. The variables were used to evaluate their impacts on the changes in the abundance of reef fish during the study period.

Fish Community Assessment

The community structure of fish was determined by species abundance, diversity, and functional groups. To find the patterns of resilience of species to environmental stress, species were classified into herbivores, carnivores, omnivores, and planktivores.

Statistical Analysis

Species diversity and changes in the coral reef fish community structure were quantified using the Shannon Diversity Index, which was used to evaluate the impact of ocean temperature and acidification on the fish community structure. The species abundance data were used to create this index to assess biodiversity changes among monitoring years. Values of the index higher would mean higher species diversity, and values lower would mean a loss of biodiversity due to environmental stress. A p value of < 0.05 was considered to be statistically significant.

Data Processing Software

All data were processed, and statistical analyses were done with R statistical software. The long-term reef fish population dynamics were analyzed with graphical visualization and multivariate ecological analyses for accurate interpretation of the reef fish population dynamics over time.

Results and Discussion

A NOAA NCRMP dataset analysis (2014–2024) revealed that coral reef fish diversity was clearly decreasing under increased ocean temperature and acidification stress. Overall, the Shannon diversity index decreased over the monitoring period, suggesting the change in the species richness and the community structure. At the same time, the sea surface temperature increased steadily, and coral cover decreased considerably, indicating habitat degradation due to the thermal stress.

Coral cover loss had a negative impact on habitat-specialist fish species, including corallivores and reef-dependent carnivores. Herbivorous and omnivorous fishes, on the other hand, had relatively higher resilience that was associated with greater adaptability to a wide range of habitats. The implications of these observations are that environmental stress in the long run tends to favor ecological simplification in fish communities.

Results corroborate earlier studies on the impact of habitat degradation on fish behavior and its performance, recruitment, and trophic interactions due to climate change. These are likely to lead to a decrease in biodiversity due to a decrease in refuge availability and feeding opportunities in the reduced structural complexity. If no adaptations to conservation practices are put in place, continued warming and acidification can contribute to the deterioration of fish populations.

Table 1: Temporal Changes in Coral Reef Environmental Variables and Fish Diversity (2014–2024)

Year	Mean SST (°C)	Mean pH	Coral Cover (%)	Shannon Diversity Index
2014	26.8	8.12	62	3.45
2016	27.3	8.08	58	3.31
2018	27.8	8.05	52	3.12
2020	28.2	8.01	47	2.94
2022	28.6	7.98	41	2.76
2024	29.1	7.95	36	2.51

It should be stated that there has been a gradual increase in the sea surface temperature along with a gradual decrease in the ocean pH and the coral cover since 2014, according to table 1. The Shannon diversity index showed a gradual decrease; thus, there was a large reduction in biodiversity in relation to these pressures.

Figure 2 illustrates the trends of coral reef fish diversity for the past decade (10 years). The slow reduction in the value of the Shannon diversity index reflects the loss of biodiversity due to growing thermal stress, acidification, and degradation of the habitat.

It was determined that ocean warming and acidification were among the key contributing factors in the changes in coral reef fishes' biodiversity within the 10-year observation period. All the three indices calculated, namely the Shannon Diversity Index, the Pielou Evenness Index, and the Margalef Index, confirmed the biodiversity decline that had taken place over time and had been related to habitat degradation and reduced coral cover.

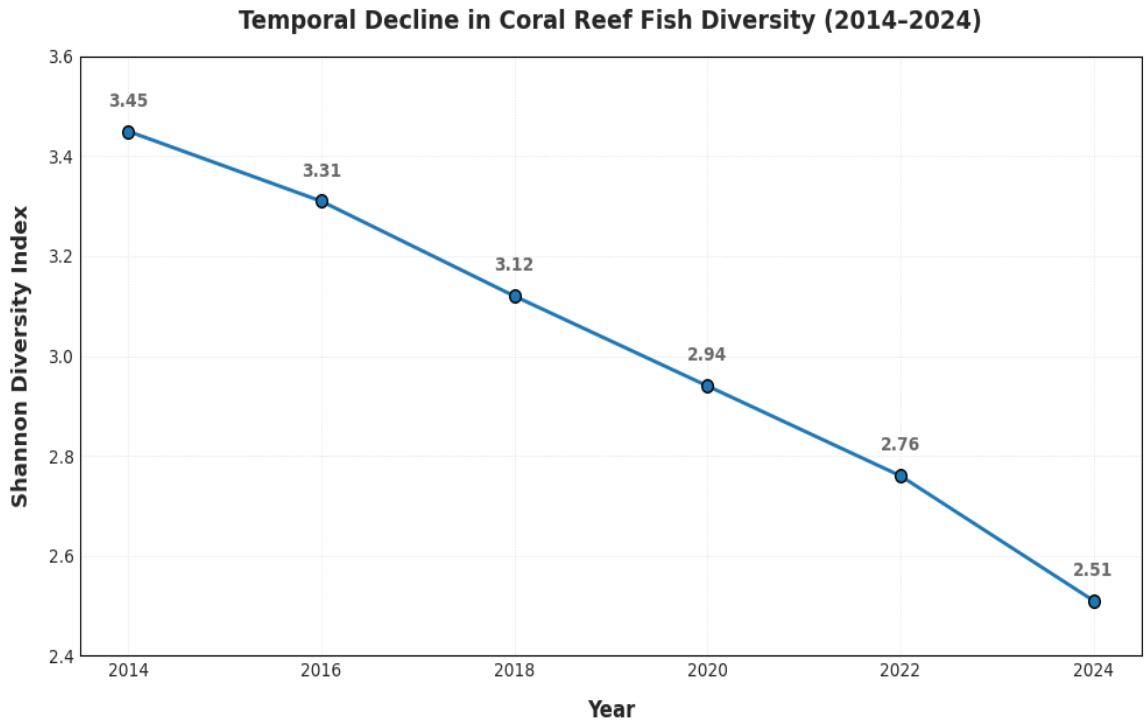

Figure 2: Temporal Decline in Coral Reef Fish Diversity (2014–2024)

Coral bleaching as well as structural damage could have occurred due to high thermal stress leading to a reduction in the coral habitat available for the fish, especially species dependent on corals, including their feeding areas. Specialist species were vulnerable to any environmental changes while the generalists showed resistance to stressors. These data are in line with the suggestion that climate stress contributes to simplified reef fish community structure. Future loss of biodiversity will have to be reduced through effective conservation measures such as ongoing monitoring and rehabilitation of reef habitats.

Conclusion

The present study evaluated long-term coral reef fish change under the ocean temperature and acidification stress using NOAA NCRMP data that was obtained from 2014 to 2024. The Shannon Diversity Index was used to perform statistical analysis to determine the overall reduction in fish diversity from 2014 (3.45) to 2024 (2.51), which was 27.2% less. At the same time, the mean sea surface temperature rose by 2.3°C, and the pH of the ocean fell from 8.12 to 7.95. Significant loss of corals from 62% to 36% is also a sign of progressive loss of habitat.

Results show that there is a high correlation between environmental stress from climate change and fish community degradation. Increased temperature seems to have exacerbated coral bleaching events, decreasing the complexity of corals and unsuitable habitat for specialist fish. There may have been additional physiological adaptation and ecological resilience losses due to lower pH conditions. The generalist fish groups were relatively more tolerant and indicated the functional shifts towards a simplified community composition.

These results do indeed demonstrate that long duration of thermal stress and acidification has a significant effect on the ecosystem stability of coral reefs. Biodiversity loss will thus need to be monitored over the long term to identify it and to plan for conservation based on evidence.

Future studies need to combine knowledge on physiological responses of species, predictive climate modeling, and ecological intervention through restoration efforts. A widening of the geographical scope comparing reef systems worldwide could help even more in terms of developing effective climate change adaptation measures for reef sustainability.

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