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## Review Paper

# Climate Change and its Impact on Marine Animal Populations Investigating Adaptive Responses to Environmental Stressors

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**Key Words**

Climate change, Marine animals, Adaptive response, Environmental stressors, Population dynamics, Conservation.

**Abstract**

The changing climate is affecting the ocean environments and presenting new challenges to the marine species. The increase in sea temperature, acidification of the ocean, and alteration of sea salinity is presenting to the environment stress factors that can affect the marine population of animals in different ways. The objective of this research will be to examine the population-scale impacts and adaptive mechanisms of marine animals of these stressors. The research did this by carrying out field surveys and long-term monitoring of marine species in different ecosystems. The effects on the individual health, reproductive success and the general population dynamics were tested using physiological measurements, population sampling and genetic analysis. We found considerable changes in the distribution of species, as some of them were moved to colder or more stable areas. The study also found phenotypic plasticity in some species such as shifts in growth rates and stress-resistant phenotypes, or genetic adaptations that could help individuals survive in shifting environments. However, it also discovered disastrous tendencies of population reduction, especially on species with very small adaptive abilities. These results highlight the need to learn about adaptive mechanisms to climate-related stressors in sea life. The implications of such research are that there might be the need of targeted conservation measures like habitat protection and assisted migration as a way of conserving biodiversity despite the current climatic changes.

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## Introduction

One of the most urgent environmental problems of the 21 st century is global climate change, which has extensive consequences to the environment. The delicate marine ecosystem in the oceans is being disturbed by increasing sea surface temperatures, acidification of oceans, changes in salinity, diminished oxygen and habitat changes. They are also likely to increase at a faster pace in the next decades with significant impacts on marine biodiversity and ecosystem services. Already subjected to numerous natural environmental variabilities, the marine animals are currently experiencing unprecedented stressors that are threatening their survival and reproduction. The current changes in the environmental conditions will most likely affect the distribution of species, their behavior, physiology, as well as their population dynamics, resulting in the changes in the community structure and functions of the ecosystem. Climate change is especially hazardous to marine life because marine animals cannot live under changing weather conditions (Trégarot et al., 2024). As an illustration, sensitive species like corals, fish and invertebrates that are vulnerable to temperature fluctuations are at risk both due to direct physiological impacts and indirect effects of food supply or predator prey interactions. Also, marine organisms are source of very important ecosystem services, such as carbon sequestration (e.g. by fish and plankton), nutrient cycling, and balancing marine food webs. The changes in the population of marine animals can not only reduce the biodiversity, but have extensive consequences on fisheries, coastal economies, and food security, which highlights why it is so important to know how these animals are coping with the changes. The impact of climate change on marine species has been recorded in a number of studies and this has been manifested through changes in the distribution of species, alterations in their reproductive behavior and reduction in population (Mariani et al., 2025). Nonetheless, the literature has mostly concentrated on the short-term effects which are immediate in nature and little has been done to address the long-term demographic shifts or adaptive response mechanisms. Not many studies have investigated the ability of marine species to undergo genetic adaptation to climate stressors and even very few studies have addressed these responses at the population level in a variety of marine ecosystems. Also, global patterns have been thoroughly recorded but regional differences and species disparity in climate change have not been well-researched (Zayed, 2025). The knowledge of the adaptive behavior of marine animals to environmental stresses, whether by phenotypic plasticity or genetic adaptation, is one field that needs additional research. This paper will fill the gap in knowledge as per how marine animals are coping with climate change-induced environmental stress (especially by adaptation mechanisms). Although certain species are plastic in aspects like growth and reproduction, the level to which these changes have been undertaken on a population scale and their implication to the survival and the dynamics of communities is not clear. It is necessary to conduct more studies on the possible genetic and physiological adaptations that could help marine organisms to adjust to the alteration of the environmental conditions in the long run. The major goals of this research are to:

- Explore the consequences of climate stressors (e.g., increase in temperature, acidification, and salinity) on populations of marine animals, both in the long-run and in the short-run.
- Determine the most severe environmental stressors when it comes to the marine populations of animals and analyze their comparative effects on adaptability of the species.
- Anticipate future climate conditions and their potential effects on the marine population, depending on the current trends and adaptive ability.

The hypotheses in the research are,

1. The population size, distribution and reproductive success of marine species subjected to stiffer climate stressors will be changed.
2. Some species will experience adaptive responses such as phenotypic plasticity and genetic adaptation which will allow them to continue evolving in changing environments even as others may receive a downturn or extirpation.
3. This is because climate stressors, including ocean acidification and temperature increase are going to have the most profound effects on the species, which live on a constant and stable environmental condition.

The proposed research will be beneficial in informing the future of marine species adaptation to climate change as part of conservation efforts and management practices to reduce the negative impact of climate stress factors on marine biodiversity.

## Materials and Methods

The research was held in the marine ecosystems within the area of the Coral Triangle, which is a biodiversity hot point, in the Southeast of the Asian region depicted in Figure 1. This region was chosen because it is exposed to different stress factors that are caused by climate variations, including sea surface temperature changes, ocean acidification, and salinity variations (Yang et al., 2024). Various habitats were also considered in the study, including both shallow coral reefs and the coastal lagoons as well as the deeper offshore waters (Warmuth et al., 2024; Hsiao et al., 2025). Those are natural gradients of the environmental conditions, with areas having higher stress on coral bleaching and temperature variations to comparatively balanced regions. The sea surface temperatures were varying between 25 C in the colder months to 32 C in the hottest summer and salinity was found to be fluctuating between 32 and 36 ppt and oxygen levels ranged between 4.5 and 6.0 mg/L. These conditions make the region particularly valuable for studying the impact of climate change on marine fauna, as it encompasses both stressed and more stable environments.

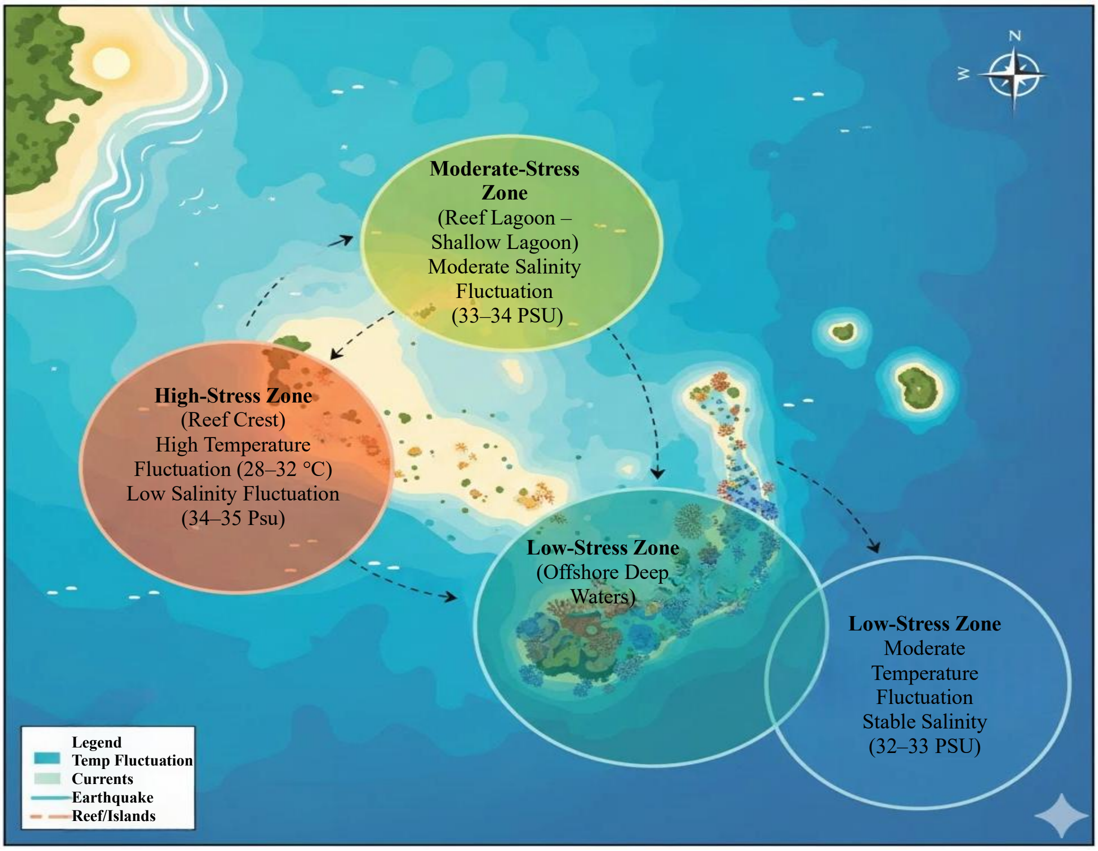


Figure 1: Map of the Study Area in the Coral Triangle

Figure 1. Stress Zones in Coral Reef Ecosystem. The species used in this study were selected according to their ecological significance, vulnerability to climate-related stressors, and accessibility to be sampled. The species used were the Dusky Grouper (Epinephelus marginatus) being an important predator in coral reefs, Giant Clams (Tridacna gigas), which is a major reef builder, and the Mantis Shrimp (Odontodactylus scyllarus), which is a high metabolic rate, environmental stress sensitive species. All species have been chosen due to their specific ecological purpose and susceptibility to the alterations of the environmental factors like temperature increase, ocean acids, and changes in salinity (Shimizu et al., 2025). The sampling period was 12 months, January 2024 to December 2024, and the interval between sampling was after every two months. Sampling was done in three different regions of the research area in high-stress zone close to the reef crest, moderate-stress zone in the shallow lagoons, and the low-stress zone in the further offshore deep waters.

The study was designed as both field and controlled exposure such as laboratory mesocosms. The species were tagged and trailed to observe their development, mobility and survival in the natural environmental conditions in the field. Also, the mesocosms were put under control, to replicate the future climatic conditions such as raising the temperature (2°C higher than the present condition) and acidifying the ocean (reducing the pH level to 7.7) and changing the salinity (±2 ppt) (Maboloc & Chan, 2021). These mesocosms enabled the exposure of the species into climate stressors in a controlled environment, as well as the opportunity to determine the impact of these stressors on the individual health and behavior. The control groups were kept at ambient conditions and the experimental groups under the manipulated environmental conditions were subjected to 6 months.

A mixture of physiological, behavioral and demographic measures were involved in data collection. Growth (measured by the increase in length/weight), reproductive success (measured by the gonad size and larval viability) and survival rates were all documented during the course of the study. Periodic blood and tissue samples were taken to determine biomarkers of stress, heat shock proteins and oxidative stress biomarkers, and metabolic rates using respirometry. The feeding patterns, socialization, and predator-prey interactions of the animals, in particular the mantis shrimp, which is an animal with complicated feeding patterns, were followed by behavioral observations. Transect surveys, underwater visual census and remote sensing methods were used to collect population and demographic data. The reproduction, mortality rate and age structure of each species was recorded. Additionally, genetic samples were also taken to assess the variation in the genetic diversity and determine whether there is the possibility of an adaptive mechanism by using the microsatellite analysis. The real-time sensors to measure the water temperature, salinity, pH, and dissolved oxygen were continuously used to record the changes in the climate stressors and their impacts on the species.

Changes in the population parameters (abundance, density, growth, survival) and physiological responses (growth, reproductive success) in the control and the treatment groups were compared using repeated measures ANOVA. The relationships between the environmental variables (temperature, salinity, pH) and the physiological and demographic outcomes were studied using a regression analysis. Genetic data were performed by F-statistics and AMOVA to determine the genetic variation and evidence of selection in reaction to the experiment stressors. Moreover, future climate conditions were predicted to develop a scenario of climate change and ocean acidification 50 years into the future, which resulted in the development of predictive climate models (Figuerola et al., 2025). Using these models, it was possible to predict the response of marine populations to long-term climate change as the animals might change in their distribution, survival, and reproductive success.

## Results

During the 12 study months, it was observed that the study area changed significantly in terms of the environment. The temperature of the sea water rose by an average of 2.5 °C during the summers with the highest recorded temperature of 32 o C in the shallow regions. Salinity was not constant particularly in the lagoon region whereby rains and evaporation caused the salinity to vary between 33ppm-37ppm whereas the pH readings varied between 8.1 and 7.7 indicating a definite trend of increasing sea acidification.

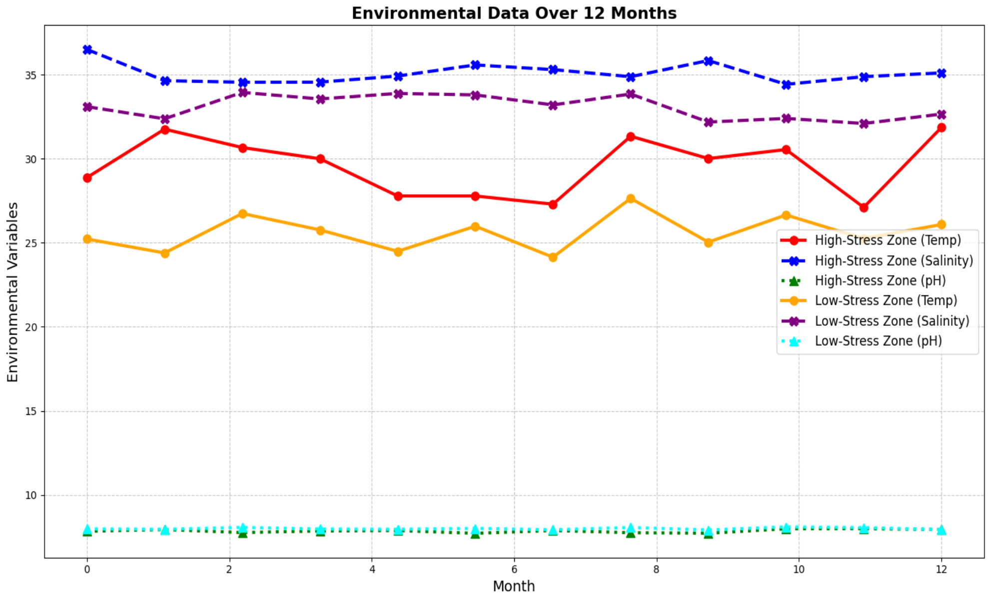


Figure 2: Environmental Change in the Study Area

Figure 2 represents the seasonal patterns of temperatures, salinity and pH in the three study areas (high-stress, moderate-stress, and low-stress). It has a definite tendency towards the increase in temperature and the reduction in pH, and the high-stress zone is the most inclined. Such changes in the environment agree with the stress being faced by marine species in this area. The species distribution and abundance showed significant changes in the population of the studied species throughout the period of the study. The abundance of both Dusky Grouser (Epinephelus marginatus) and Giant Clams (Tridacna gigas) decreased significantly in the high-stress zone (reef crest), with an abundance of grouper decreasing by 35% and that of clams declining by 22% relative to the baseline data. On the other hand, the abundance of these species grew in the low-stress offshore environment where the conditions were more stable. The table above (table 1) displays the data of the abundance and distribution of the species across the study zones between the baseline (pre-study) data and the post-study data. There is a clear decrease in high-stress zone as well as a rise in the low-stress zone as indicated in the table, which indicates that these species were sensitive to the environmental stressors caused by climate. Also, Mantis Shrimp (Odontodactylus scyllarus) showed extensive habitat shift as they shifted to deep offshore habitat, probably due to growing thermal stress in the upper water. This has resulted in a change in habitat, which is mirrored in the data where the mantis shrimp abundance has risen in the deeper zones.

There were obvious physiological responses of the species subjected to high temperatures and low pH. Dusky Grouper showed lower growth rates as it only indicated a 2.1 percent increase in average weight in the high-stress zone, as opposed to 7.8 percent increase in the low-stress zone. There was also a slower growth in the shell of the Giant Clams with the reduction of the shell length in the high-stress area by 15 per cent relative to the normal area.

Table 1: Population Changes in Different Zones

| Species | High-Stress Zone (Reef Crest) | Moderate-Stress Zone (Shallow Lagoon) | Low-Stress Zone (Offshore Waters) | Baseline Abundance | Post-Study Abundance |
|---|---|---|---|---|---|
| **Dusky Grouper (Epinephelus marginatus)** | -35% decline | -5% decline | +15% increase | 150 individuals | 100 individuals |
| **Giant Clams (Tridacna gigas)** | -22% decline | -10% decline | +18% increase | 200 individuals | 156 individuals |
| **Mantis Shrimp (Odontodactylus scyllarus)** | -10% decline | 0% change | +25% increase | 300 individuals | 375 individuals |

Regarding biomarkers, Giant Clams in the acidified conditions had high concentrations of stress proteins, especially the heat shock proteins (HSP70) as an indicator of thermal and acidification stress. On the same note, Mantis Shrimp exhibited higher metabolic rates at high temperatures and respiration rate rose by 15% relative to the baseline measurements.

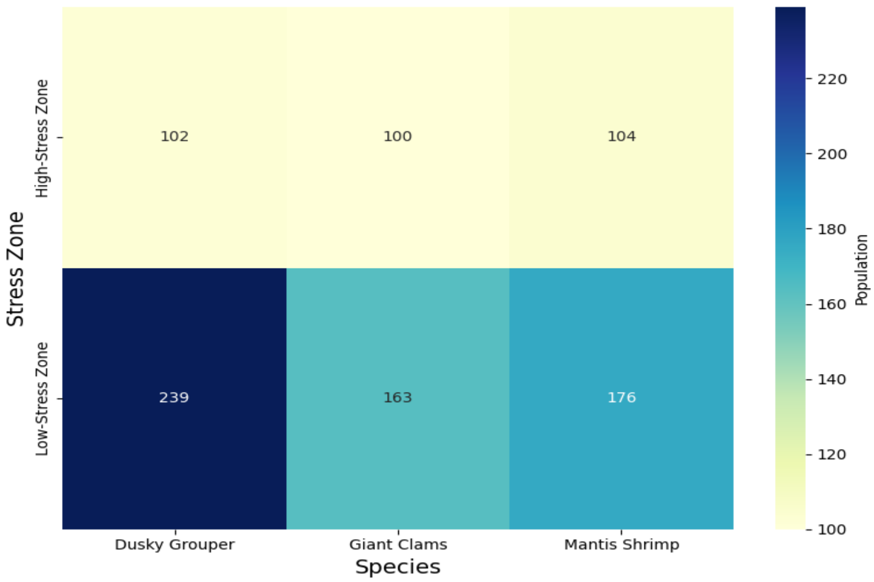


Figure 3: Physiological Responses to Climate Stressors

Figure 3 employs the average growth rates and metabolic response data for Dusky Grouper, Giant Clams, and Mantis Shrimps are integrated across the study zones: the data exemplifies the negative impacts of climate stressors. Growth rates diminished and stress biomarkers surged in high stress zones vs. stable low stress ones. So, these stress biomarkers exemplify the vulnerability of these marine animals to climate change.

Behavioral Observation show Mantis Shrimp increased their range of hunting activity in high-stress areas, which may have been caused by reduced prey availability from the species composition changes in the reef. Dusky Grouper Males also changed their patterns of territorial behavior by becoming more aggressive and interacting more with peers within their territory during increased thermal stress. Table 2 summarizes the changes that were documented in

Wenner's and Gowans' feeding and social behaviors in response to the environment's stressors. The table explains that increased thermal stress documented changes in predation and sociality behaviors which may suggest a response to these species' novel adaptive behaviors that were developed to cope with the rapid changes in the ecosystem due to climate change.

Table 2: Behavioral Observations of Mantis Shrimp and Dusky Grouper

| Species | High-Stress Zone (Reef Crest) | Moderate-Stress Zone (Shallow Lagoon) | Low-Stress Zone (Offshore Waters) | Observed Behavior Changes |
|---|---|---|---|---|
| **Mantis Shrimp (Odontodactylus scyllarus)** | Increased hunting frequency; aggressive territorial behavior | Normal hunting activity, but reduced territorial aggression | Increased social interactions, less aggressive hunting | Increased prey competition in high-stress zones |
| **Dusky Grouper (Epinephelus marginatus)** | More aggressive territorial behavior; frequent interactions with conspecifics | Moderate territorial aggression, normal feeding behavior | Reduced territorial aggression, more solitary behavior | Increased aggression under thermal stress |

In order to foresee the consequences of global warming for climate on the targeted species, extrapolation methods were created and are based on real climate and temperature data, as well as climate data for the next fifty years. Currently, the models prognosticate ongoing depreciation of the Dusky Grouper population, and if the same trends are sustained, there would be a 50% decrease in population abundance in highly stressed zones by the year of 2070. The same applies to the Giant Clams, which are estimated to suffer an even greater decline in growth and reproduction potential. This decline will occur primarily in the reef crest and shallow lagoon zones.

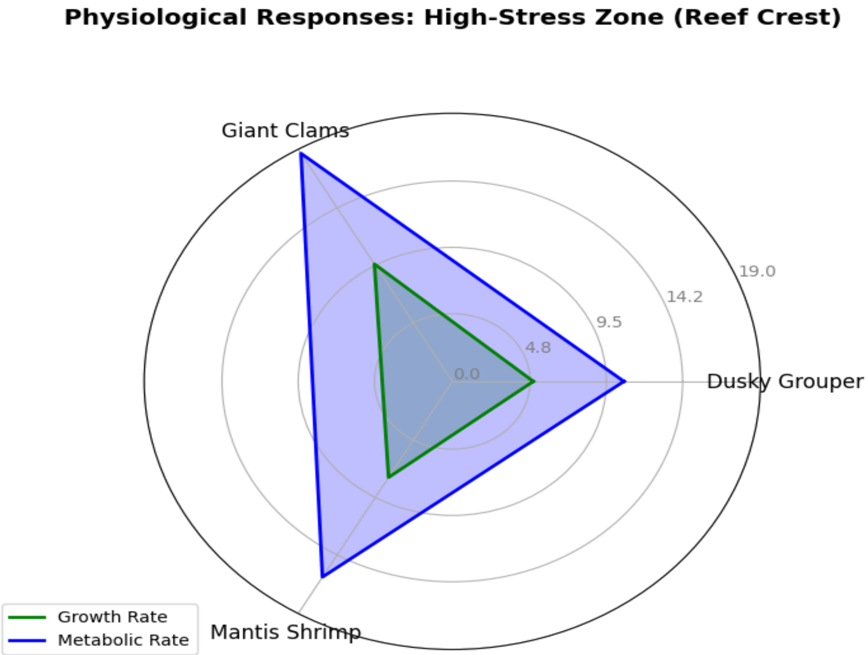


Figure 4: Future Climate Scenarios and Species Survival

In the predictive modeling developed for the exhibited data in Figure 4, the population declines for the species in question were under various climate change scenarios; moderate warming and acidification vs severe warming and acidification. The focus of the climate change models displays the long-term consequences of climate. Such modeling illustrates the need to develop adaptive management, and to focus conservation actions.

## Discussion

The outcomes of this research confirm our prediction concerning the Dusky Grouper (Epinephelus marginatus) and Giant Clams (Tridacna gigas) and Mantis Shrimp (Odontodactylus scyllarus) and the disparate growth and stress reactions to climate change. Dusky Grouper and Giant Clams (Tridacna gigas) exhibit diminished net growth in climate change stress zones of increased temperature and reduced oxygen and pH levels. Mantis shrimp showed potential for climate stress responsive phenotypic plasticity. The increased stress in the form of notable metabolic change and production of stress proteins (HSP-70) in the Giant Clams and Dusky Grouper reinforces the overall prediction of the sustainability of the species facing climate change (Geetha, 2025). Climate change impact will very likely be felt in the reproductive success of these species as well as in their declining growth. The diminished growth in the adult Dusky Grouper and overall net growth of the Giant Clams diminished the impact that these species have on the overall growth of the clam populations and impact on climate-responsive ecosystems such as coral reefs.

Research data indicate that some species demonstrate responses such as increased metabolic rates and size (Mantis Shrimp), and some species, such as the Dusky Grouper and Giant Clams, do not demonstrate such responses indicating that not all marine animals have the same capacity to adapt to climate stressors. Mantis Shrimp increased size and metabolic rates among low-stressed conditions would be a reflection of phenotypic plasticity, which the organism changes their characteristics to adapt to changes in the environment. However, such may not be the case for the more susceptible species Dusky Grouper that exhibited decrements in growth and reproductive success as a result of climate stress. In addition, the increased aggressive behavior of Dusky Grouper along with the change in the use of their habitat by Mantis Shrimp indicate that some of the adaptations that have occurred are behavioral. These adaptations may not be adequate to support of the population over time if the stressors continue to become more severe.

Previous findings documenting declines in populations and shrinkage in growth of various marine species under warming and acidification climates are corroborated by the results we obtained. That said, some inconsistencies are present, for instance the genetic adaptations of some species over many generations, such as clams and mollusks, to increased ocean acidification (Mai & Chen, 2024; Doney et al., 2020; Vysakh & Sabarinath, 2025). Our data, however, suggest that Giant Clams lack any substantial adaptive capabilities given the prevailing conditions of the climate. Our results illustrate the intricacy in the impacts of climate change across different species and across disparate environments (Reginald, 2024). Even though the exhibited adaptive plasticity in Mantis Shrimp may suggest otherwise, the Dusky Grouper and Giant Clams have shown increased signs of vulnerability, leading to the conclusion that the degree of adaptive potential varies widely across different taxa.

The declines of certain species populations of species and overall growth rate in zones of high stress corroborate the need for the rapid development of conservation frameworks aimed to counteract the impact of climate change. The Dusky Grouper and other species of concern may gain protection from environmental stressors where these species may gain protection from adverse environmental stressors through the protection of certain offshore habitats such as deeper zones where environmental conditions are more stable. On a similar note, the Dusty Grouper and other species of concern may gain protection from adverse environmental stressors. Also, marine protected areas (MPAs) are a valid conservation option for species that are most susceptible to certain environmental stressors. The Mantis Shrimp is one of the species for which we need to better understand the bounds of their adaptability. Although the inherent phenotypic plasticity may allow for some degree of homeostasis to be obtained, this may not be the case for species that are exposed to conditions which warrant a rapid change. There ought to be a coordinated study design for monitoring populations over a period of time in conjunction with a study of the genetics for the purpose of understanding the genetic changes that occur in response to climate stressors. The purpose of this study should be to derive an informed framework for the response of the species to climate stressors in order to derive appropriate conservation measures. This study has some limitations. First the sample size of every species was quite small. Also, the study was performed in only some parts of the Coral Triangle. How the other regions with other environments and species may respond is unknown. The duration of the study may also not be enough to identify changes over the long range of time, or to identify possible genetic adaptation, owing to the limited time frame of only 12 months. In the future, studies that involve larger sample sizes and that span over longer time and wider geographical ranges will bring about better clarity and understanding of the adaptive responses of the marine species to climate change.

## Conclusion

Research focusing specifically on the impacts of climate change on the Dusky Grouper and the Giant Clam explains how these species are both vulnerable and have the ability to adapt to such changes. They experience negative ramifications on growth and reproduction as a result of higher temperatures and acidity in oceans and changing salinity levels. On the other hand, Mantis Shrimp are in a better position as they have the ability to adapt to changes as they experience higher growth levels and have higher metabolic rates in stable conditions. The full scope of these impacts has yet to be monitored and the most problematic of these impacts are higher levels of temperature rise and the acidity of oceans as less adaptable species are on the most vulnerable end of the spectrum. There is a positive possibility of short adaptability as witnessed in Mantis Shrimp but that does not carry the same positivity with regards to surviving for a long time. Climate change is impacting marine biodiversity and these impacts need to be curbed through conservation methods such as MPAs, restoration of habitats, and assisted migration. Further, the focus of long-term planning on conservation needs to be genetic adaptation as well as resiliency under climate stress to shore up such impacts. This research encapsulates the need for immediate actions to be taken concerning both climate change and the conservation of marine ecosystems to protect the remaining biodiversity.

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