Investigating the Influence of Environmental and Anthropogenic Pressures on the Biodiversity of Key Sessile Taxa in Coral Reef Ecosystems: A Focus on Porifera and Rhodophyta

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Declaration

I declare that the raw data was provided by Ransome, Emma from Imperial College London.
I declare that I was responsible for all the data processing.
I declare that no mathematical models were developed by me or my supervisor.
My supervisor James Rosindell provided me with technical Q&A support and feedback in developing the analyses presented.

Abstract

This study investigates the impact of environmental stress factors and human activities on the biodiversity of the two main sessile constituents, Porifera(Sponge) and Rhodophyta(Red algae), in coral reef. The biodiversity, including species richness (represented by Hill number when $q = 0$) and evenness (represented by Hill number when $q = 1$), was assessed using the Hill number, and a random forest model was employed to identify factors that significantly influence abundance. Subsequent regression analyses were conducted separately on abundance and its influencing factors under different species. The results indicate that the presence of environmental stress variables, specifically stressors, leads to a decrease in the species richness and evenness of Porifera and Rhodophyta. In terms of anthropogenic pressures, the analysis concluded that fishing intensity is the most significant factor affecting the species richness and evenness of these two species. The study then analyzed the overall impact of human pressure on biodiversity, and the results unexpectedly showed a positive correlation. This result may be because moderate disturbance can enhance environmental heterogeneity and support certain species, or it may be due to limited sample size or more complex nonlinear relationships. However, further research is needed to determine whether this correlation reflects actual ecological patterns or sampling bias. Overall, the findings concerning environmental stress variables and fishing intensity can help guide more targeted measures to mitigate stressors and control fishing intensity for more specific coral conservation strategies. Additionally, the overall analysis of human pressure factors suggests future research directions, which will involve exploring more non-linear models to investigate deeper and more complex relationships between human pressure factors and biodiversity.

1 Introduction

Coral reefs are vital ecosystems that support extensive biodiversity and provide essential services, such as coastal protection, food resources, and economic benefits through tourism and fisheries. However, these ecosystems are increasingly under threat from both global environmental changes and local human activities. Environmental stressors, such as rising sea surface temperatures (SST) and prolonged thermal stress measured through degree heating weeks (DHW), are major drivers of coral bleaching and biodiversity loss, leading to disruptions in coral reef communities (Williamson et al., 2022). Simultaneously, human pressures like coastal development, pollution, and overfishing further exacerbate reef degradation, making these ecosystems particularly vulnerable (Andrello et al., 2022).

This study focuses on two dominant groups of sessile organisms found in coral reefs: sponges (Porifera) and red algae (Rhodophyta). These taxa are critical to reef ecosystem functioning, contributing to nutrient cycling, habitat provision, and primary production (Bell et al., 2014; Nelson, 2009). Despite their ecological significance, the responses of these organisms to both environmental and anthropogenic pressures have been less studied compared to corals, leaving gaps in our understanding of how these taxa contribute to overall reef resilience.

In this context, the present study aims to separately analyze the effects of environmental stressors and human activities on the diversity of Porifera and Rhodophyta. By examining these pressures independently, this study seeks to determine how each set of variables influences the species richness and evenness of these key reef organisms. Such an approach is important because environmental and anthropogenic pressures can have

different modes of action and intensity, which may affect biodiversity in distinct ways (Williamson et al., 2022; Andrello et al., 2022).

First, regarding environmental pressures, it is hypothesized that stressor variables, particularly temperature-related factors like SST anomaly(Sea surface temperature anomaly) and DHW(degree heating weeks), will negatively impact the species richness (when Hill Number $q = 0$) and species evenness (when Hill Number $q = 1$) of Porifera and Rhodophyta (Hill, 1973). This hypothesis is grounded in extensive research showing that elevated temperatures and thermal stress are associated with significant biodiversity loss and shifts in community structure, primarily through mechanisms such as coral bleaching and reduced habitat availability (Hoegh-Guldberg et al., 2007).

For anthropogenic pressures, the focus is specifically on factors such as coastal development and fishing intensity. Based on existing literature, this study hypothesize that fishing intensity will have the most significant impact on the biodiversity of Porifera and Rhodophyta, given its well-documented role in altering trophic dynamics and reducing species diversity in reef ecosystems (Andrello et al., 2022). Additionally, it is expected that all anthropogenic variables will negatively correlate with both species richness and evenness, with fishing pressure anticipated to be the dominant factor due to its widespread and direct effects on reef community structure. (Mora et al., 2006).

To test these hypotheses, this study employs Hill Numbers as metrics for assessing species richness (Hill Number $q = 0$) and species evenness (Hill Number $q = 1$) (Hill, 1973). By focusing on the dominant sessile taxa, Porifera and Rhodophyta, within coral reef ecosystems, this research offers initial insights into how various environmental and anthropogenic pressures influence species richness and evenness in these key groups, contributing to a deeper understanding of the factors shaping biodiversity patterns in coral reef communities.

2 Methods

This study was conducted across multiple coral reef sites as part of the global FutureReef project, which aims to assess the impacts of environmental and anthropogenic pressures on coral reef biodiversity. This paper will concentrate on sessile organisms, specifically Porifera and Rhodophyta, due to their dominance in reef communities as shown in Figure 1. Genetic data from DNA metabarcoding were combined with environmental and human pressure metrics. Next, Hill numbers were calculated to assess species diversity, and Random Forest models were used to identify key stressors. Beyond that, linear regression was made use of to explore the straight connections between Hill number and numerous affecting factors individually, while Generalized Ingredient Versions (GAMs) were utilized to additionally check out the nonlinear relationships within the information. The findings for were visualized to highlight critical aspects impacting coral reef health and strength.

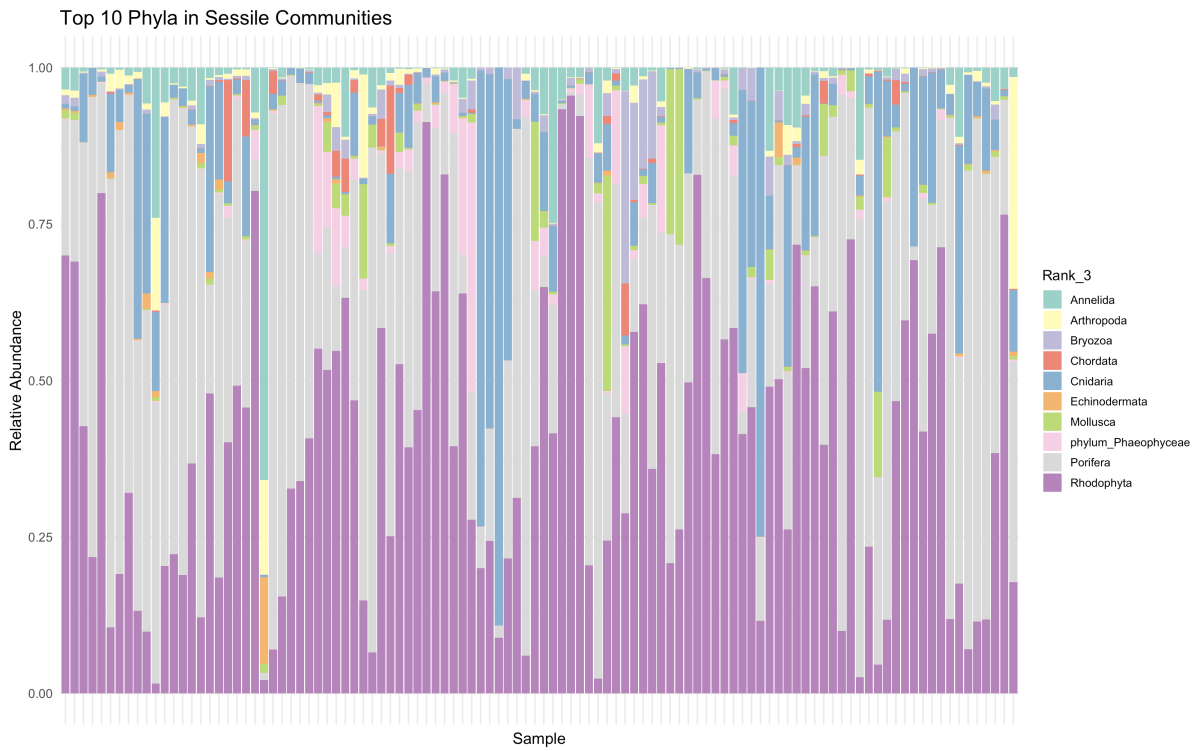

Figure 1: The top ten phyla with the highest relative abundance. Porifera and Rhodophyta are the two most abundant species in the sessile, with the relative abundance of Porifera being 0.38 and that of Rhodophyta being 0.34.

2.1 Genetic Data Collection and Processing

Sessile organisms were sampled using Autonomous Reef Monitoring Structures (ARMS) deployed at various reef sites. Upon retrieval, sessile fractions from these ARMS units were processed for genetic analysis. The cytochrome oxidase I (COI) gene was targeted for DNA metabarcoding, and Operational Taxonomic Units (cOTUs) were identified based on sequence similarity. This provided a detailed overview of species composition and relative abundance at each site.

2.2 Environmental and Anthropogenic Pressure Data

2.2.1 Environmental Stress Exposure (SE Scores)

Environmental stress at each site were quantified using the Reef Environmental Stress Exposure Toolbox (RESET), which aggregates data on nine key environmental factors which divided into Stressor and Reducer (See Table 1). Each variable is assigned a Stress Exposure (SE) score based on specific thresholds, reflecting the degree of environmental stress at a site. These scores were determined using ecological thresholds obtained from the literature and were calculated using a fuzzy logic approach to account for varying intensities(Williamson et al., 2022). In order to facilitate integration with diversity data, this part of the data will be processed using quarterly averages. Calculating averages by seasonal classification can balance the impact of different seasons, capture potential seasonal patterns, and make the results more comparable between different samples.

Table 1: Codes and Descriptions for Environmental Factors

Codes	**Stress category**	**Descriptions**
cloud	Reducer	Cloud cover
wind	Stressor	Wind speed
depth	Stressor	Ocean depth at the location of the coral reefs
current*	Reducer	The continuous movement of seawater in a specific direction
salinity*	Stressor	The concentration of dissolved salts in the ocean
DHW	Stressor	Degree heating weeks
SST	Stressor	Sea surface temperature
SST_anomaly	Stressor	The deviation of the sea surface temperature from its long-term average or expected value for a specific region and time of year
SST_variability	Reducer	The fluctuations or changes in sea surface temperatures over time and across different spatial scales

*Note: Due to the nearly empty datasets for ocean currents and salinity collected in this project, these two variables were excluded from the study.

2.2.2 Anthropogenic Pressure Data

Anthropogenic pressures were assessed using the global map of human pressures on coral reefs. This dataset includes factors such as coastal population density, tourism and industrial development (see Table 2). Each variable was assigned an anthropogenic stress score(Andrello et al., 2022), which quantifies the cumulative impact of human activities on the reef environment.Each variable is assigned an anthropogenic stress score based on a percentile approach, ranking the intensity of each stress relative to the global distribution. This approach allows for comparison of stresses across variables while minimizing the impact of outliers.

Table 2: Codes and Descriptions for Anthropogenic Factors

Codes	**Descriptions**
grav_NC	Fishing
pop_count	Coastal development
num_ports	Industrial development
reef_value	Tourism
sediment	Sediment
nutrient	Nitrogen

2.3 Hill Numbers for Biodiversity Assessment

Hill numbers ($q = 0, 1$) were calculated to assess the diversity of Porifera and Rhodophyta at each site, based on the relative abundance of Operational Taxonomic Units (cOTUs) derived from COI metabarcoding data. Hill numbers provide a versatile measure of diversity by adjusting the sensitivity to species abundances. When calculating Hill numbers, the following general formula can be used:

$$^{q}D = \left(\sum_{i=1}^{S} p_i^q \right)^{\frac{1}{1-q}}$$

Where:

- S is the total number of species in the community.
- p_i is the relative abundance of species i, where $p_i = \frac{n_i}{N}$, with n_i being the number of individuals of species i, and N the total number of individuals in the community.
- q is a parameter that determines the sensitivity to species abundances.

Special Cases:

- When $q = 0$:

$$^{0}D = \sum_{i=1}^{S} p_i^0 = S$$

  In this case, the Hill number simply counts species richness, i.e., the number of species present in the community, without considering their abundance distribution.

- When $q = 1$:

$$^{1}D = \exp\left(-\sum_{i=1}^{S} p_i \ln p_i \right)$$

  In this case, the Hill number is the exponential form of Shannon entropy, which allows for a balanced consideration of both species richness and evenness.

In this study, Hill numbers ($q = 0$ and $q = 1$) were calculated for the Porifera and Rhodophyta-associated communities. First, OTUs classified as Porifera and Rhodophyta at Phylum were extracted from the taxonomy table of phyloseq object and the OTU table was converted into a matrix format. Then, the relative abundance of each OTU in each sample was calculated. For Hill number $q = 0$, the number of OTUs with non-zero relative abundance in each sample was determined. For Hill number $q = 1$, Shannon entropy was computed and then exponentiated to obtain the result. Finally, all calculated results were saved in a data frame along with the sample IDs for subsequent analysis. In this paper, $q = 0$ represents species richness, and $q = 1$ represents species evenness.

2.4 Statistical Analysis

2.4.1 Random Forest Modeling

Random forest model, being a set knowing approach, combines multiple decision trees to boost anticipating precision and robustness, making it fit for dealing with complicated environmental datasets with possible communications amongst predictors. It was employed to identify the most crucial environmental and anthropogenic variables influencing the Hill numbers for Porifera and Rhodophyta. The versions were run separately for each and every taxon and Hillside number (q = 0, 1).

The formula made use of in the Random Forest versions included all possible stress factors - both environmental (e.g., sea surface area temperature, cloud cover, wind speed) and anthropogenic (e.g., coastal development , Industrial development , tourism) - as forecasters. The importance of each variable was determined by its mean decrease in accuracy, a metric that reflects the reduction in version accuracy when a particular variable is excluded. This approach allowed us to rank the variables according to their relevance scores, highlighting the most influential aspects for every Hill number and taxon.

To concentrate on one of the most crucial variables, the relevance scores were ordered in descending order, and a collective significance rating was determined. A limit was evaluated 90% advancing significance, guaranteeing that just the most crucial variables– those that collectively added to the majority of the design's anticipating power– were preserved. This technique not just streamlines the model by reducing dimensionality yet likewise enhances interpretability, making it simpler to determine essential stressors influencing coral reef biodiversity.

2.4.2 Linear Regression Model

After recognizing key variables through Random Forest modeling, linear regression models were used to explore the direct connections between these stress factors and Hill numbers. The procedure started by carrying out single-variable linear regressions for each vital predictor recognized by the Random Forest models. Predictors were categorized as significant or insignificant based on their p-values, with a significance threshold set at $p \leq 0.05$.

Significant variables were after that included in a multivariate straight regression design, which was additional fine-tuned using stepwise regression. The step-by-step method, directed by the Akaike Details Criterion (AIC), iteratively added or got rid of variables to accomplish the optimal equilibrium in between model intricacy and fit. AIC is a commonly utilized criterion in version choice, punishing models for the variety of specifications to prevent overfitting.

To address the possible concern of multicollinearity amongst predictors, Variation Rising cost of living Variables (VIF) were calculated. VIF measures just how much the variance of a regression coefficient is pumped up due to collinearity with various other forecasters. Variables with high VIF values (typically above 10) were sequentially gotten rid of from the version to make sure that the final version was both durable and interpretable. This step is vital as multicollinearity can misshape the estimated coefficients and jeopardize the design's predictive capability.

The final linear regression models provided insights into the direct linear effects of various stressors on the diversity metrics of Porifera and Rhodophyta, helping to identify which anthropogenic and environmental pressures are most strongly associated with

changes in species richness, evenness.

2.4.3 Generalized Additive Modeling (GAM)

To capture non-linear relationships between stressors and Hill numbers, Generalized Additive Models (GAMs) were applied, particularly focusing on variables that were identified as insignificant in the linear regression models. GAMs are highly flexible models that allow for smooth, non-linear relationships between the predictors and the response variable by fitting spline functions to the data.

For each predictor, different smoothing parameters (k-values) were tested to determine the best fit, based on the Akaike Information Criterion (AIC). The choice of k-value controls the flexibility of the spline; lower k-values lead to smoother, less flexible fits, while higher k-values allow the model to capture more complex patterns in the data.

The initial GAM models included all potential non-linear predictors in Linear model. The models were then refined through a stepwise selection process, where non-significant smooth terms were removed. This iterative process ensured that only the most relevant non-linear effects were retained, providing a more parsimonious and interpretable model.

The final GAM models not only quantified the non-linear influences of stressors on biodiversity but also provided visualizations of these relationships. These visualizations illustrated how different stressors might have complex, non-linear impacts on the diversity of coral reef communities.

3 Results

3.1 Important Variables Selected by the Random Forest Model

3.1.1 Environmental Pressure

The random forest model identified the most important environmental variables under different taxonomic groups and Hill numbers (see Figure 2). For Porifera, when Hill number $q = 0$, the most influential variable is SST_anomaly, followed by cloud, wind, SST, and DHW. When $q = 1$, SST has the greatest impact, followed by cloud, DHW, wind, and SST_anomaly. For Rhodophyta, at $q = 0$, SST_anomaly is the most significant variable, followed by SST, SST_variability, cloud, and DHW. At $q = 1$, SST_anomaly remains the key variable, followed by SST, DHW, cloud, depth, and SST_variability. Overall, SST-related variables consistently dominate across different taxonomic groups and Hill numbers, highlighting their crucial role in determining the environmental pressure on biodiversity.

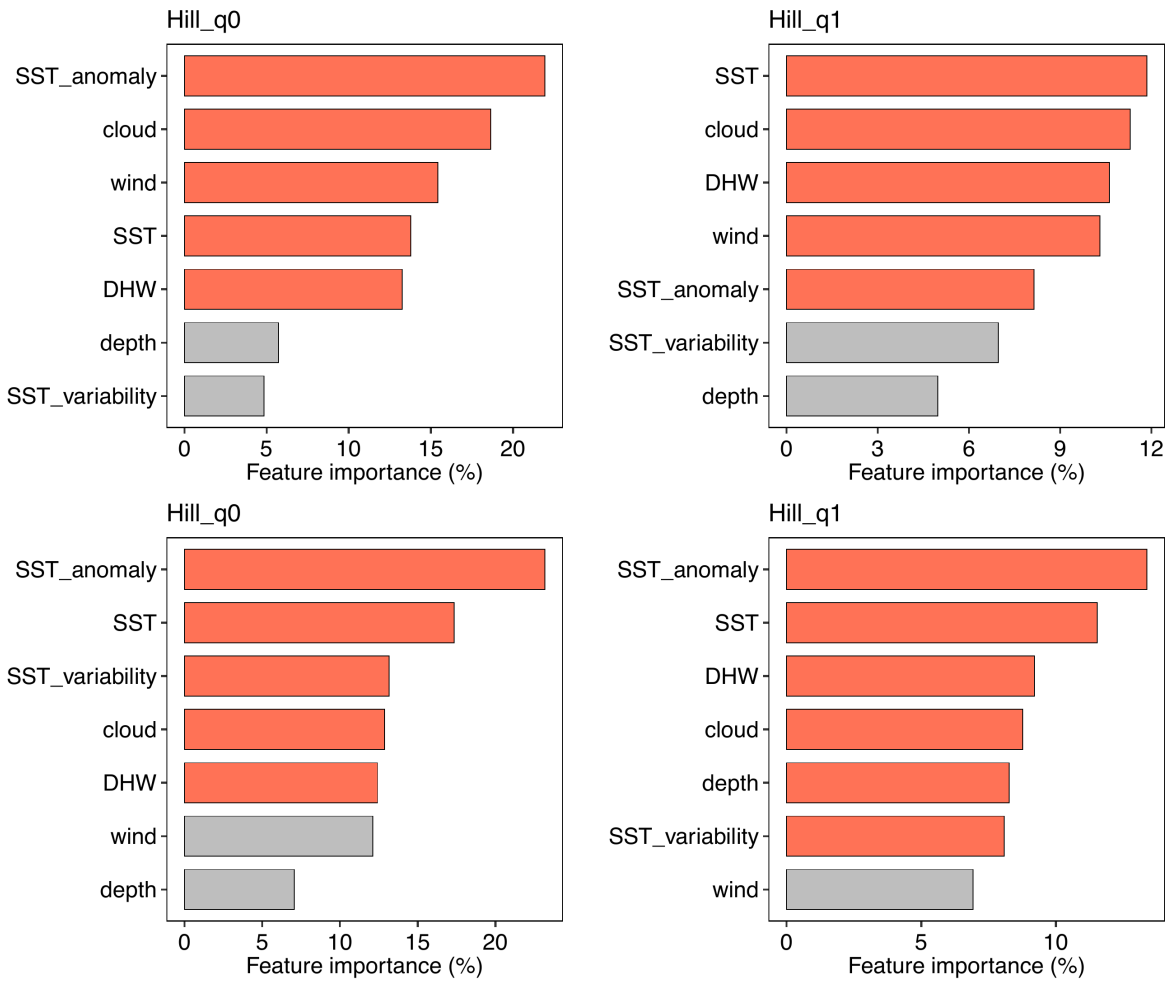

Figure 2: Important variables for environmental. The first row in the figure shows the feature importance for Porifera, while the second row displays the importance for Rhodophyta. The orange bars indicate the key variables identified by the random forest model. The horizontal axis represents the impact of each variable on the Hill number, with larger values indicating a stronger influence. The vertical axis ranks the features, with those having the greatest effect on the Hill number positioned at the top.

3.1.2 Anthropogenic Pressure

The random forest model also highlighted the key anthropogenic variables under different taxonomic groups and Hill numbers (see Figure 3). For Porifera, when Hill number $q = 0$, pop_count is the most influential variable, followed by sediment and grav_NC. When $q = 1$, pop_count remains the most significant variable, followed by reef_value and grav_NC. For Rhodophyta, at $q = 0$, grav_NC is the dominant variable, followed by sediment and pop_count. At $q = 1$, grav_NC remains the key factor, followed by reef_value and sediment. These results emphasize that population density (pop_count) and gravel-related factors (grav_NC) are consistently critical in explaining anthropogenic pressure on biodiversity across different groups and Hill numbers.

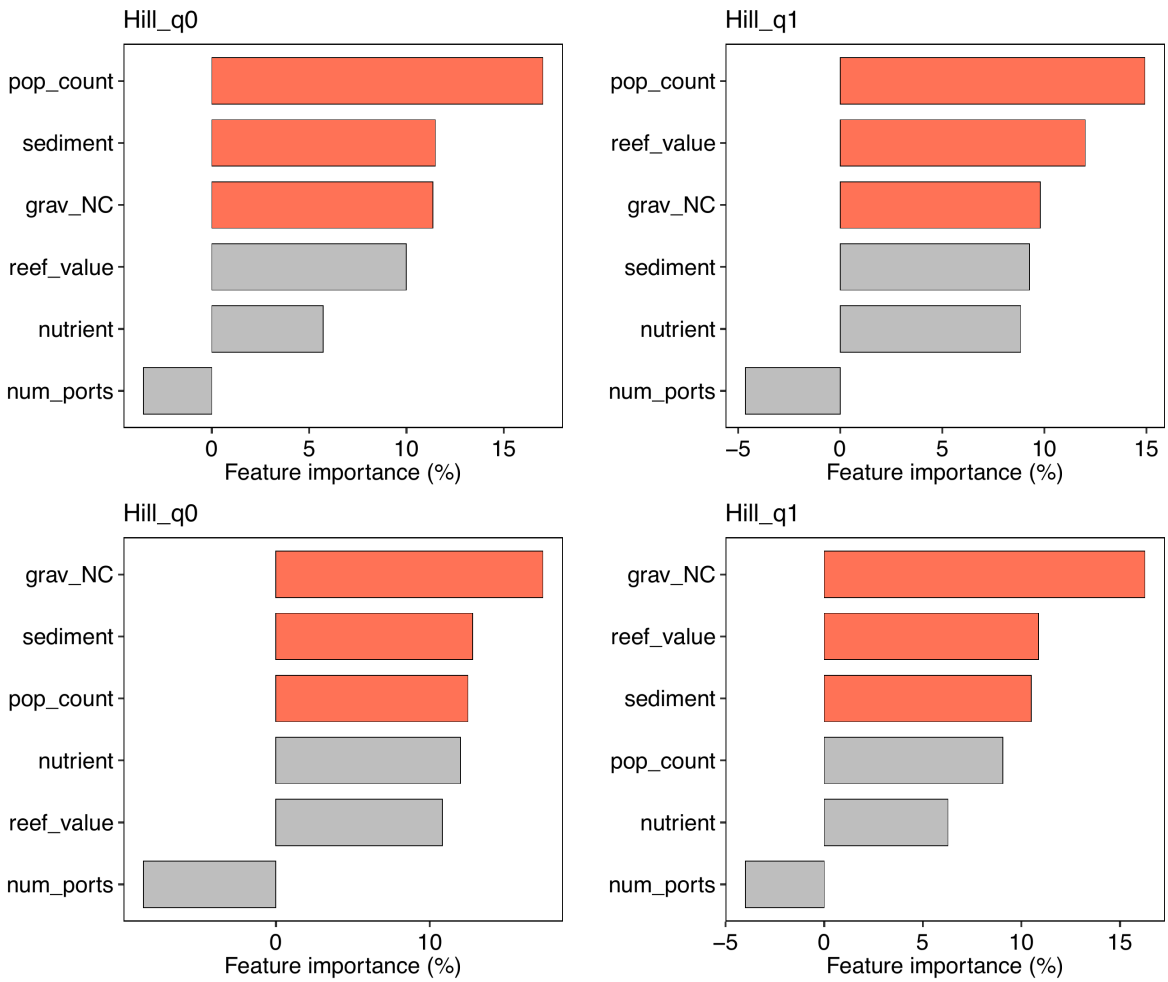

Figure 3: Important variables fot anthropogenic.The first row in the figure shows the feature importance for Porifera, while the second row displays the importance for Rhodophyta. The orange bars indicate the key variables identified by the random forest model. The horizontal axis represents the impact of each variable on the Hill number, with larger values indicating a stronger influence. The vertical axis ranks the features, with those having the greatest effect on the Hill number positioned at the top.

3.2 Results: Influence of Environmental Pressures on Porifera and Rhodophyta Diversity

In the linear regression analysis for Porifera Hill numbers ($q = 0$ and $q = 1$), the results revealed significant relationships between three environmental variables and $Hill_q0$ (see Figure 4). Single-variable regression analysis indicated that cloud cover was significantly negatively correlated with $Hill_q0$ ($R^2 = 0.20$, $P < 0.001$), suggesting that increased cloud cover is associated with lower species richness. Wind speed showed a positive correlation with $Hill_q0$ ($R^2 = 0.13$, $P < 0.001$), indicating that higher wind speeds might promote species richness. Sea surface temperature (SST) also exhibited a positive correlation with $Hill_q0$ ($R^2 = 0.15$, $P < 0.001$), though the relationship was weak, suggesting that SST may only influence species richness within a certain range. In the multiple linear regression analysis, the initial model included cloud, wind, and SST as predictors. Cloud remained significantly negatively associated with $Hill_q0$ ($P = 0.007$), while wind

and SST were not statistically significant. After stepwise selection, the final model retained cloud and wind as predictors, with cloud showing a stronger negative correlation ($P < 0.001$) and wind approaching significance ($P = 0.053$). The adjusted R^2 of the final model was 0.2092, indicating that these variables together explain approximately 21% of the variance in $Hill_q0$. Additionally, for $Hill_q1$, the single-variable regression showed a significant negative correlation with Degree Heating Weeks (DHW), a known stressor variable, with $R^2 = 0.07$ and $P = 0.006$, indicating that higher cumulative thermal stress is associated with lower species evenness.

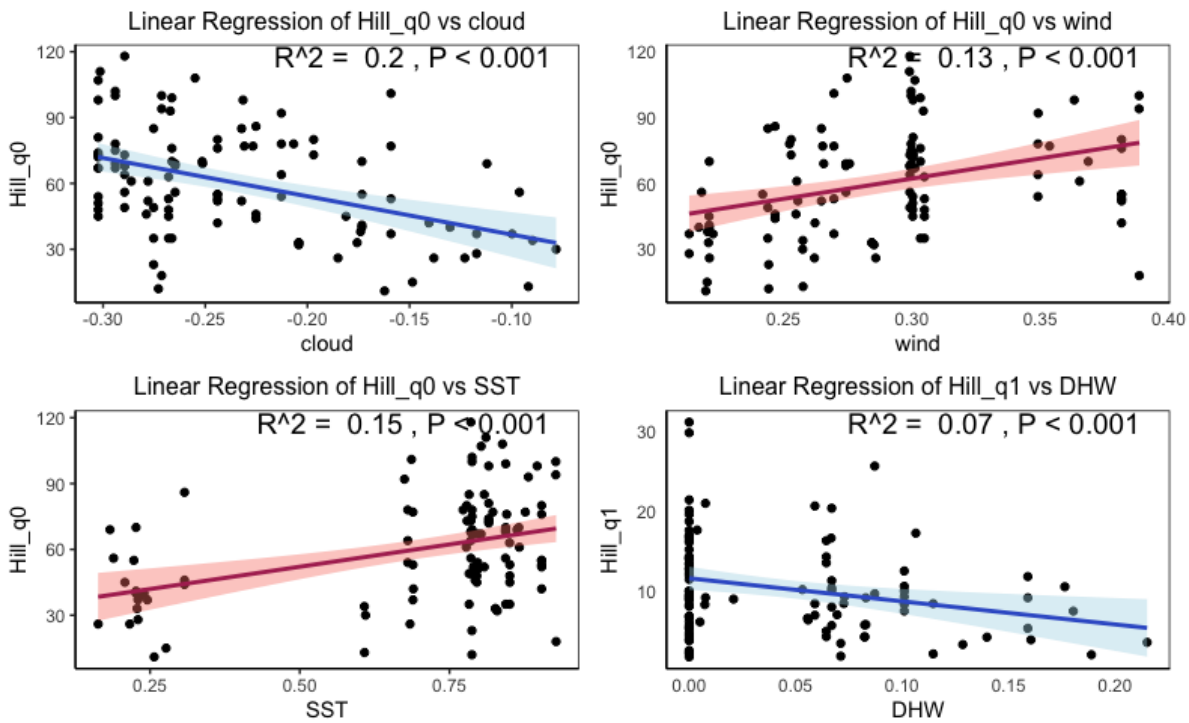

Figure 4: The hill number in the linear regression of Porifera's environmental pressure variables has a significant linear relationship when $q = 0$, $q = 1$

In the linear regression analysis for Rhodophyta Hill numbers ($q = 0$ and $q = 1$), single-variable regressions identified four significant environmental variables for $Hill_q0$: SST_anomaly, SST, SST_variability, and DHW (see Figure 5). Among these, SST anomaly exhibited a significant negative correlation with $Hill_q0$ ($R^2 = 0.28$, $P < 0.001$), suggesting that greater deviations from average SST are associated with reduced species richness. SST also showed a negative correlation with $Hill_q0$ ($R^2 = 0.07$, $P = 0.006$), indicating that higher SST could negatively impact species richness. Conversely, SST_variability displayed a positive but weak correlation with $Hill_q0$ ($R^2 = 0.04$, $P = 0.037$), suggesting that fluctuations in SST might contribute to greater species richness. Lastly, DHW showed a negative relationship with $Hill_q0$ ($R^2 = 0.06$, $P = 0.013$). In the multiple linear regression analysis, the initial model included SST_anomaly, SST, SST_variability, and DHW. Among these, SST_anomaly had the most significant negative impact on $Hill_q0$ ($P < 0.001$), while SST approached significance ($P = 0.069$). After stepwise selection, the final model retained SST_anomaly and SST, both of which had significant negative relationships with $Hill_q0$ ($P < 0.001$ and $P = 0.005$, respectively). The adjusted R^2 of the final model was 0.3225, indicating that these variables explain approximately 32%

of the variance in $Hill_q0$. For $Hill_q1$, single-variable regressions indicated significant negative correlations with SST_anomaly ($R^2 = 0.08$, $P = 0.003$) and DHW ($R^2 = 0.05$, $P = 0.025$), suggesting that greater thermal anomalies and cumulative heat stress are associated with lower species evenness. The initial multiple linear regression model included both SST_anomaly and DHW, where SST_anomaly was the only significant variable ($P = 0.044$). In the final model after stepwise selection, SST_anomaly remained significant ($P = 0.003$), explaining approximately 7.5% of the variance in $Hill_q1$.

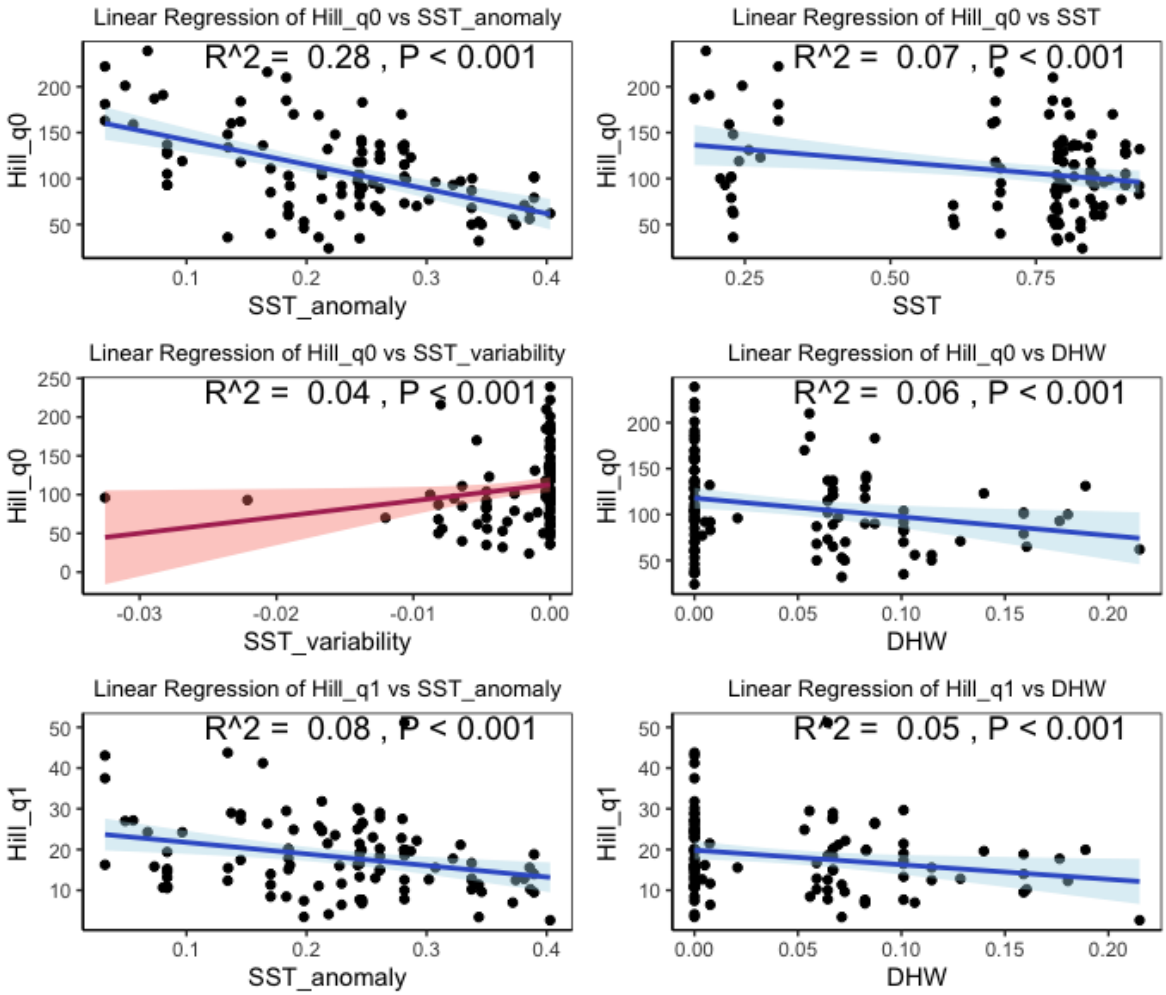

Figure 5: The hill number in the linear regression of Rhodophyta's environmental pressure variables has a significant linear relationship when $q = 0$, $q = 1$

In summary, for Porifera at $q = 0$, none of the three significant variables (cloud, wind, SST) align with the initial hypotheses, while at $q = 1$, the results are consistent with the expected relationships. For Rhodophyta, both $q = 0$ and $q = 1$ show results that align with the initial hypotheses. Specifically, stressor variables such as SST_anomaly and DHW have significant negative impacts on species richness and evenness, while SST_variability shows a positive effect, which is consistent with its hypothesized role as a reducer.

3.3 Results: Influence of Anthropogenic Pressures on Porifera and Rhodophyta Diversity

In Porifera, simple linear regressions revealed significant positive relationships between species richness ($Hill_q0$) and coastal development ($R^2 = 0.41, p < 0.001$), sediment pollution ($R^2 = 0.36, p < 0.001$), and fishing pressure ($R^2 = 0.29, p < 0.001$) as shown in Figure 6. However, in the multiple regression model, only coastal development remained significant ($\beta = 27.12, p = 0.00775$), indicating that Porifera species richness is primarily influenced by higher population densities in coastal areas. The stepwise regression further confirmed coastal development as the dominant driver, while sediment pollution ($\beta = 14.17, p = 0.132$) was retained but with a weaker and non-significant effect. Additionally, the generalized additive model (GAM) showed a significant nonlinear relationship between fishing pressure and species evenness ($Hill_q1$) ($p < 0.001$), where low levels of fishing pressure corresponded with increased evenness, followed by a decline as pressure intensified.

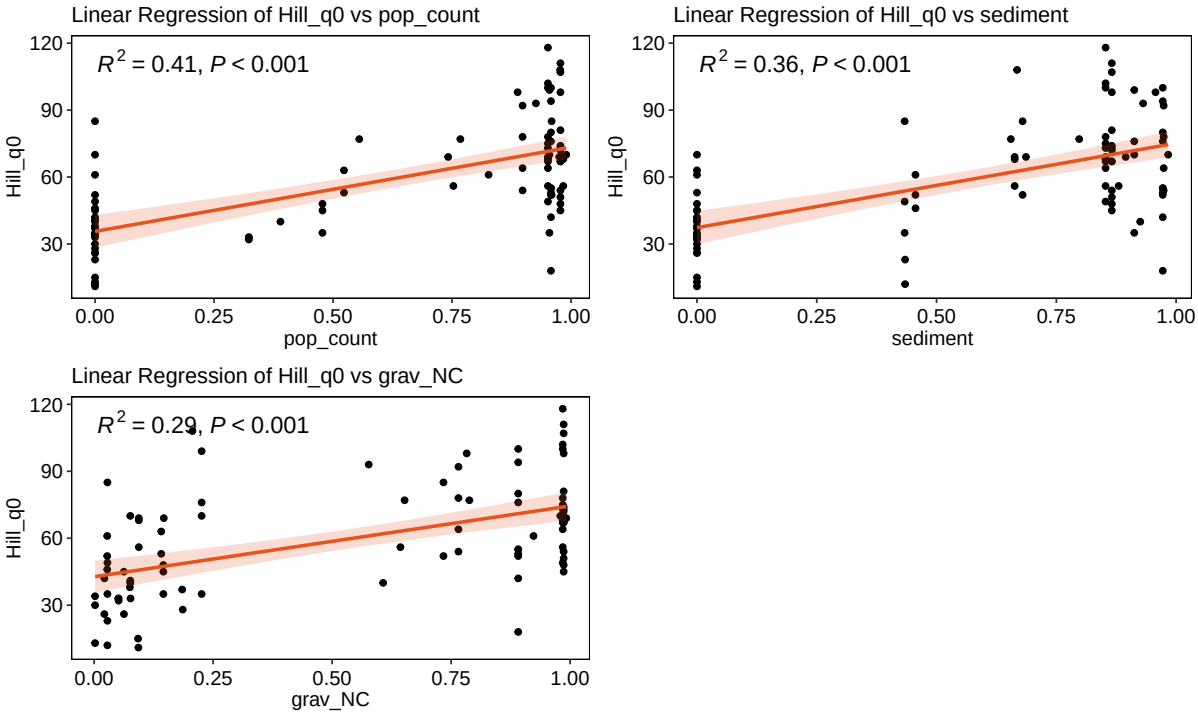

Figure 6: The hill number in the linear regression of Porifera's anthropogenic pressure variables has a significant linear relationship when $q = 0$, $q = 1$

For Rhodophyta, linear regression similarly indicated positive associations between species richness ($Hill_q0$) and all three pressure variables: sediment pollution ($R^2 = 0.20, p < 0.001$), coastal development ($R^2 = 0.19, p < 0.001$), and fishing pressure ($R^2 = 0.17, p < 0.001$) as shown in Figure 7. However, in the multiple regression model, none of these variables remained significant ($p > 0.20$), suggesting potential collinearity among predictors. The stepwise regression ultimately identified sediment pollution as the main factor driving species richness in Rhodophyta ($\beta = 45.00, p < 0.001$). The GAM analysis further revealed a similar nonlinear response of species evenness ($Hill_q1$) to fishing pressure ($p = 0.003$), where evenness initially increased at lower fishing levels before declining as pressure intensified.

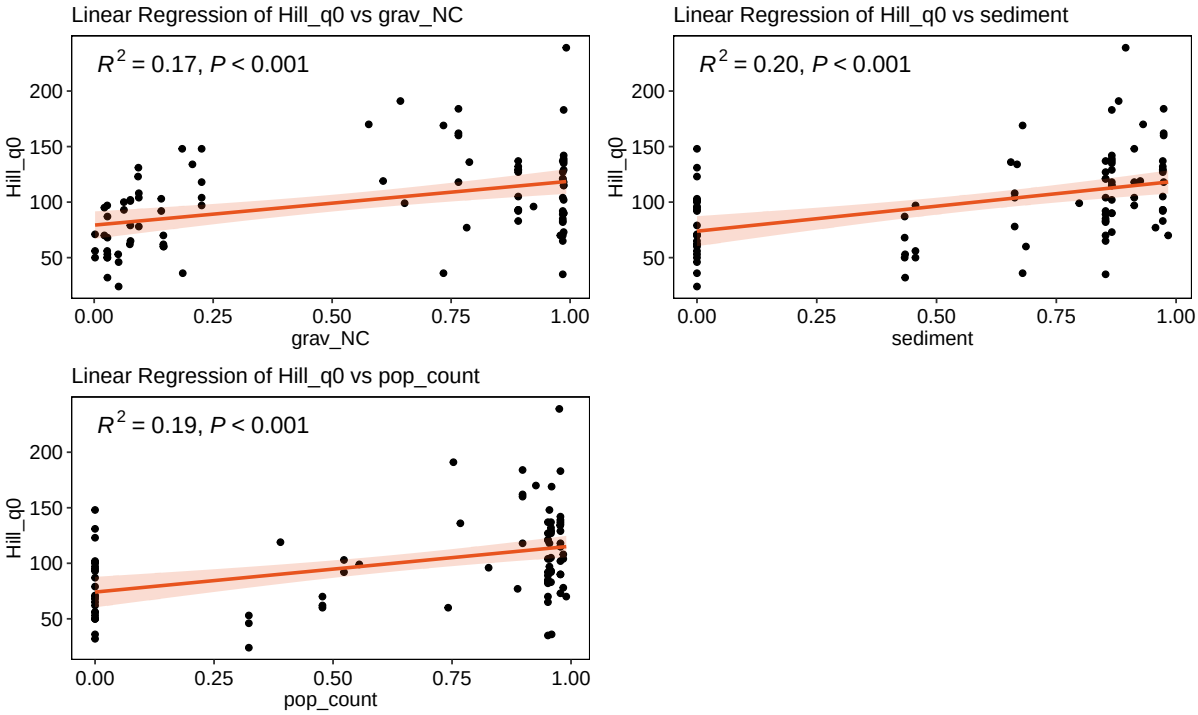

Figure 7: The hill number in the linear regression of Rhodophyta's anthropogenic pressure variables has a significant linear relationship when $q = 0$, $q = 1$

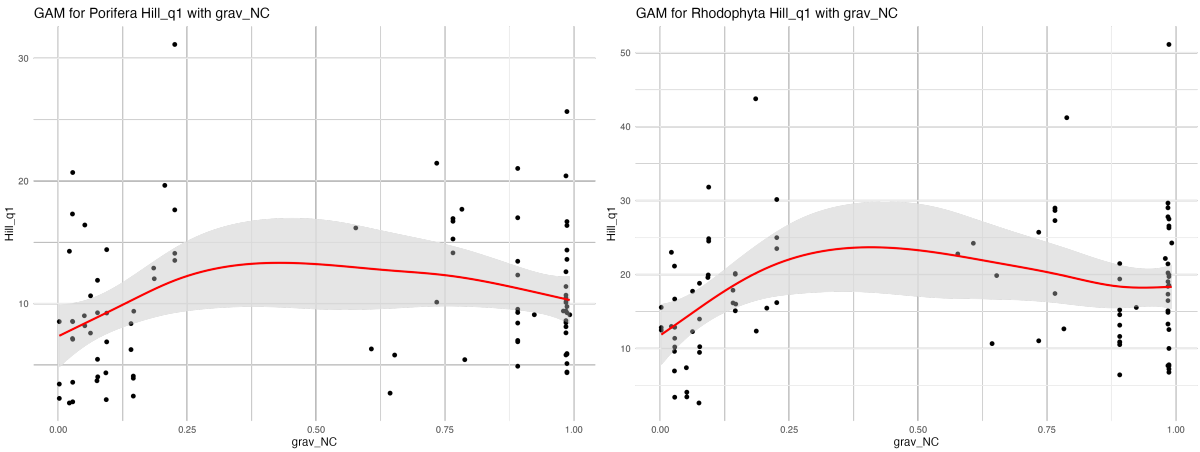

Figure 8: When Hill number $q = 1$, fishing has a significant nonlinear relationship

In the analysis of $Hill_q0$, both Porifera and Rhodophyta showed positive correlations with pressure variables, contradicting our hypothesis of a negative relationship (see Figure 8). However, the GAM models for $Hill_q1$ revealed similar nonlinear patterns in both taxa, suggesting that moderate levels of fishing pressure may enhance species evenness, while higher pressure results in a decline.

4 Discussion

This study examined the effects of environmental and anthropogenic stressors on species richness and evenness in Porifera and Rhodophyta. As hypothesized, temperature-related

stressors such as SST anomalies and DHW were generally negatively correlated with biodiversity, especially for Rhodophyta. However, for Porifera, initial assumptions were challenged. Regarding anthropogenic stressors, although fishing intensity was expected to be the main factor affecting both taxa, results indicated that Costal Development had the greatest impact on sponges. In addition, although human pressure is hypothesized to be negatively correlated with species richness and evenness, moderate levels of pressure can sometimes lead to increases in diversity, suggesting that anthropogenic pressure is not necessarily entirely detrimental to biodiversity.

4.1 Environmental Pressures on Diversity

The relationship between environmental variables and Porifera richness ($Hill_q0$) reveals some interesting deviations from the initial hypotheses, particularly regarding cloud cover and wind, both of which show unexpected correlations. The negative correlation between cloud cover and Porifera's richness may be explained by considering the impact of light availability on primary productivity. Increased cloud cover reduces the amount of sunlight penetrating the water column, which in turn decreases the efficiency of photosynthesis, particularly for primary producers such as algae and phytoplankton (Gattuso et al., 1998). A reduction in primary productivity could lead to a decline in overall food web productivity, indirectly affecting the availability of organic particles that sponges rely on for nutrition. Sponges are filter feeders that depend on suspended organic matter, and diminished light could reduce their food supply by lowering the abundance of particulate organic matter. Additionally, increased cloud cover might result in localized cooling, which could alter water density, stratification, and circulation patterns—factors that are crucial for the survival of certain sponge species (Tomczak & Godfrey, 2003).

Conversely, wind speed, initially categorized as a stressor, showed a positive correlation with Porifera's richness, suggesting a more nuanced role in these ecosystems. Enhanced wind speeds increase surface water turbulence and vertical mixing, potentially bringing nutrient-rich deep waters to the surface, thereby boosting phytoplankton growth (Behrenfeld et al., 2006). Greater primary productivity translates into higher concentrations of organic particles in the water column, providing more food for filter-feeding sponges. Moreover, stronger water flow enhances the circulation of these particles, improving the efficiency of sponge feeding and supporting their overall abundance. Additionally, increased water movement aids in the dispersal of sponge larvae, contributing to greater species richness across broader spatial scales (Maldenado, 2006). These findings underscore the complex and context-dependent effects of wind on marine ecosystems, where the expected stressor role might shift to a beneficial one depending on the ecological context.

In contrast to Porifera, the results for Rhodophyta align more closely with initial hypotheses. Both SST_anomaly and DHW, recognized as stressors, show significant negative correlations with species richness and evenness, consistent with their well-documented impact on coral reef ecosystems (Hughes et al., 2018). Rhodophyta, being primarily benthic algae, are sensitive to temperature extremes and prolonged heat stress, which can lead to bleaching and a loss of diversity. On the other hand, SST_variability, acting as a reducer, positively correlates with species richness, suggesting that moderate temperature fluctuations could enhance adaptive capacity and resilience (Maynard et al., 2008). This highlights the importance of considering both absolute stress levels and environmental variability in understanding ecosystem responses.

Overall, while Rhodophyta follows more predictable ecological responses, Porifera exhibits more complex interactions with environmental factors, particularly in relation to cloud cover and wind. These findings suggest that simple classifications of stressors and reducers may not be universally applicable across taxa and that detailed species-specific analyses are essential for accurate predictions. Future research should focus on exploring potential nonlinear dynamics and interactions between multiple stressors, as well as the role of local environmental conditions, to refine our understanding of these complex relationships (Harley et al., 2006).

4.2 Anthropogenic Pressures on Diversity

The positive correlations observed between variables such as coastal development and sediment pollution with species richness ($Hill_q0$) in both Porifera and Rhodophyta are counterintuitive, given that these pressures are generally expected to degrade habitats and reduce biodiversity (Halpern et al., 2008). While, this also contradicts the earlier hypothesis that anthropogenic pressures would suppress the biodiversity of Porifera and Rhodophyta. One possible explanation is that moderate levels of these pressures may enhance environmental heterogeneity, providing a wider range of niches and supporting greater species richness (Tittensor et al., 2009). For example, coastal development can increase nutrient inputs into the marine environment, potentially benefiting certain filter feeders like Porifera by boosting food availability (Fabricius, 2005). Similarly, low levels of sediment input might create more diverse microhabitats, which could promote the co-existence of different Rhodophyta species. However, these positive relationships should be interpreted with caution. In some cases, they may reflect the spatial concentration of conservation efforts or sampling biases in areas that are subject to higher levels of human activity but also receive more management attention (Wilson et al., 2007). Additionally, these results do not necessarily imply that such pressures are beneficial to overall ecosystem health, as increases in species richness may be driven by opportunistic species that thrive under disturbed conditions (McKinney & Lockwood, 1999), often at the expense of more sensitive species.

The random forest models revealed that coastal development (pop_count) was the primary factor influencing both species richness ($Hill_q0$) and species evenness ($Hill_q1$) in Porifera, while fishing pressure (grav_NC) was the dominant variable for Rhodophyta. This divergence can be attributed to the distinct ecological characteristics and functional roles of these taxa. Porifera, as sessile filter feeders, are directly influenced by water quality and nutrient availability, both of which are closely linked to coastal development. Increased population densities along coastlines often lead to higher nutrient runoff and organic matter inputs, which can enhance food supply for sponges (Cebrian et al., 2010). Coastal development can also lead to more complex habitat structures, such as artificial substrates, that Porifera can colonize (Bell et al., 2015). These factors might explain why coastal development emerged as the most significant driver of Porifera diversity, suggesting that in regions with moderate anthropogenic activity, sponges could experience a net benefit from increased resources and substrate availability. In contrast, Rhodophyta, being primary producers, are more directly affected by fishing activities that alter the trophic structure and light availability in reef ecosystems (Burkepile & Hay, 2008). Fishing pressure often reduces herbivorous fish populations, leading to less grazing on algae and allowing certain Rhodophyta species to proliferate (Mumby et al., 2006). Additionally, the removal of large predatory fish can shift community dynamics in a way that

favors algal growth, particularly in areas with high fishing pressure. This trophic cascade effect may explain why grav_NC was identified as the key variable for Rhodophyta. However, as fishing pressure continues to increase, the dominance of opportunistic species can lead to reduced evenness and overall biodiversity decline, as indicated by the nonlinear responses observed in the GAM analysis.

Despite the unexpected positive relationships in species richness, the GAM analysis for species evenness ($Hill_q1$) revealed a more nuanced pattern consistent with our original hypothesis. For both Porifera and Rhodophyta, low to moderate levels of fishing pressure initially led to an increase in evenness, likely due to the reduction of dominant competitors and the release of resources. However, as fishing pressure intensified, evenness declined sharply, reflecting the loss of species and overall ecosystem degradation. This pattern aligns with the "intermediate disturbance hypothesis" (Connell, 1978), which posits that biodiversity is maximized at intermediate levels of disturbance, where neither competitive exclusion nor high mortality dominates the community structure.

This finding is supported by other studies in coral reef ecosystems, where overfishing has been shown to lead to declines in functional diversity and overall species evenness (Mouillot et al., 2013). The fact that this feedback was consistent for both Porifera and Rhodophyta underscores the broad applicability of this eco-friendly principle and suggests that fishing pressure is an important factor that should be managed scientifically to avoid biodiversity loss.

4.3 Implications for Coral Reef Management

This research highlights the distinct yet interconnected impacts of environmental and anthropogenic pressures on main sessile biodiversity. The significant influence of environmental variables, such as SST_ anomaly and DHW, on species richness and evenness in Rhodophyta and Porifera underscores the urgent need for climate change mitigation. Sessile of coral reefs are extremely conscious temperature fluctuations, with extended heat stress bring about decreases in biodiversity and environment health and wellness (Hoegh-Guldberg et al., 2007). Reducing greenhouse gas emissions is therefore critical for long-term reef protection. Lowering greenhouse gas exhausts is therefore critical for long-lasting coral reef security. In addition, boosting durability via proactive administration techniques– such as broadening marine secured areas (MPAs) and implementing active repair campaigns– can assist buffer coral reefs versus the intensifying threats presented by environment change (Edgar et al., 2014).

Pertaining to anthropogenic pressures, the study determined coastal development and fishing as key drivers of biodiversity patterns in Porifera and Rhodophyta. Coastal development (pop_count) became the main element affecting Porifera diversity, likely because of increased nutrient overflow and habitat alteration in established areas(Fabricius, 2005). Effective land-use monitoring methods, including the establishment of buffer zones, stricter zoning regulations, and boosted wastewater therapy, are necessary to mitigate these impacts and preserve reef communities. Alternatively, fishing pressure (grav_NC) had the most obvious effect on Rhodophyta, affecting both species richness and evenness. Overfishing can cause trophic inequalities and changes in neighborhood structure, frequently leading to algal prominence and lowered reefs cover(Mumby et al., 2006). Sustainable fisheries management, including catch restrictions, gear restrictions, and the security of herbivorous fish populations, is essential for maintaining healthy reef communities. Furthermore, engaging neighborhood communities in the monitoring pro-

cedure and promoting eco-friendly practices can improve conformity and guarantee long-term preservation success (Mora et al., 2006).

4.4 Limitation and Future Research Directions

While this study provides valuable insights into the impacts of environmental and anthropogenic pressures on coral reef biodiversity, further research is needed to fully understand these complex dynamics. First, the analysis predominantly relies on linear and additive models, such as generalized additive models (GAMs) and linear regressions, which may oversimplify the complex interactions among environmental variables. Coral reef ecosystems are highly dynamic, with non-linear relationships, threshold effects, and interactive stressor impacts playing significant roles in shaping species richness and evenness. Future studies should explore the application of more advanced non-linear models, including machine learning algorithms and other non-parametric techniques, to better capture these complexities and potential tipping points in reef ecosystems.

Additionally, the generalizability of our findings across different regions and species remains uncertain. The relationships observed between anthropogenic pressures and biodiversity metrics may be specific to the taxa and geographic areas studied. Coral reef ecosystems are highly diverse and exhibit significant regional variability in species composition, historical disturbance regimes, and local adaptation. Expanding the geographical and taxonomic scope of future analyses would be essential for determining whether these patterns hold true across different coral reef systems globally. Such efforts could involve cross-regional comparisons and meta-analyses that account for varying environmental and socio-ecological contexts.

Finally, while our study identified key drivers of biodiversity for Porifera and Rhodophyta, the interactions between different stressors were not fully explored. Human activities and environmental changes often act synergistically, exacerbating their collective impact on ecosystems. Future research should focus on multi-stressor analyses that incorporate both direct and indirect effects, allowing for a more comprehensive understanding of how combined pressures influence coral reef resilience. This would be particularly relevant in the context of climate change, where rising temperatures interact with local stressors such as overfishing and pollution, leading to cumulative impacts.

5 Conclusion

This study examined the distinct effects of environmental and anthropogenic pressures on coral reef biodiversity, focusing separately on Porifera and Rhodophyta. Environmental stressors, such as SST anomaly and DHW, were found to have significant negative effects on species richness and evenness, particularly for Rhodophyta, consistent with the well-documented impacts of thermal stress on coral reef ecosystems. In contrast, anthropogenic pressures like coastal development and fishing intensity emerged as critical drivers of biodiversity changes, with coastal development primarily affecting Porifera and fishing pressure having the greatest impact on Rhodophyta. Although our hypothesis predicted negative correlations between these stressors and biodiversity metrics, the results showed unexpected positive correlations, suggesting that moderate levels of these pressures may, under certain conditions, enhance species richness or evenness. This highlights the complexity of human impacts on reef ecosystems, where factors such as nutrient

inputs from coastal development or shifts in trophic dynamics due to fishing can produce context-dependent and non-linear outcomes.

These findings highlight the importance of addressing both environmental and anthropogenic stressors in conservation strategies. Effective management requires targeted actions such as reducing local pollution, regulating coastal development, and implementing sustainable fishing practices, alongside broader efforts to mitigate climate change. By focusing on these distinct drivers, the coral reef ecosystems can be better protected and their biodiversity can be maintained in the face of increasing environmental challenges.

6 Data and Code Availability

All data and codes in this project are available at:
https://github.com/ghy113/CMEECourseWork/tree/main/Project

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