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Assessing the Threat of Coral Decline on Fish Diversity in Response to Temperature

Ryland Talmadge
SIT Study Abroad

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Zanzibar Coastal Ecology and Resource Management

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Advisor: Mohammed Suleiman

Academic Director: Dr. Nat Quansah

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1.0 Acknowledgements

This study would not have been possible without the guidance, support, and resources of many individuals whom I would like to thank. Firstly, I wish to express my sincere gratitude to the rangers at Misali- Haji, Mohammed, Saidi, and Hamis- for their boundless insight and knowledge about the island, and for ensuring our safety and happiness at all times. Secondly, I wish to thank Dr. Suleiman and Dr. Nat for their academic guidance and constructive feedback throughout this study. I would also like to thank Said Omar and the SIT Staff for organizing the logistics of our studies and offering support during the study period. Additionally, I would like to thank the government of Zanzibar for permitting me to conduct this research. Finally, I would like to thank the "Misalians"-Julianna, Aisha, and Faith- for making our time on the island truly memorable.

2.0 Abstract

Misali, a PECCA-protected island off the east coast of Pemba, Tanzania, is considered to be a marine biodiversity hotspot with a protected Non-Extractive Zone (NEZ) and remaining Extractive Zone (EZ). Upon protection, the island's fringe reefs faced severe coral bleaching during the 1998 bleaching event, estimated to kill up to 70% of corals. Since the event, several others have occurred in addition to restructuring the management plan in 2006 to expand the region to 1000km^2. While the damage from the most recent coral bleaching event in 2020 has yet to be surveyed, this study investigates the current reef health in reflection of temperature differences caused by the western NEZ zone's proximity to the cold upwelling of the Pemba Channel. In doing so, reef health was defined as high levels of rugosity, low levels of bleaching, and high levels of fish diversity and abundance. These variables were examined independently and concurrently to understand their interdependency and relationships. Once established, reef health was further analyzed in two different temperature zones to understand how reef health in a higher temperature range in the EZ would differ from the reef health in the colder temperature range in the NEZ. Over a 22-day period, 2,799 fish from 24 different families were surveyed along 30 transects split evenly between the NEZ and EZ. For each transect, environmental data were collected, reef rugosity and coral bleaching percent cover estimated, and fish counted according to the pre-established family guide. Statistical significance was found between temperature measurements in the NEZ and EZ, effectively confirming the hypothesis that reefs in the NEZ would inhabit cooler temperatures. Additionally, several families exhibited statistical significance between the two zones, with more inhabiting NEZ reefs. While coral bleaching percent cover was found to have no significant difference between the two zones, the trends expressed graphically identify a relationship between rugosity, bleaching, and fish abundance. The results not only supported the assertion that the three variables shared a correlation with one another but further indicated that reef health as identified above, was stronger in the NEZ cooler waters than in the EZ warmer waters. Thus, this study identifies anthropogenic threats to coral reef ecosystem resiliency on Misali Island in hopes of informing future conservation efforts of Zanzibar's reefs and beyond.

3.0 Introduction

Coral reef habitats are among the most biodiverse in the world, housing nearly a quarter of all marine life (Obura and Grimsditch, 2009). Coral reefs are an essential part of coastal communities as more than 500 million people globally rely on coral reef ecosystems as sources of income, food security, storm protection, and leisure. It is estimated that their resources and services generate approximately 2.7 trillion US dollars annually, despite their decline (GCRMN, 2022).

In fact, one-third of coral reefs globally have died over the last 40 years, and a further third are currently endangered due to exponentially increasing environmental and anthropogenic stressors (Meissner, 2012). Climate Change is now regarded as the most serious and impending threat to coral reefs as it threatens the ecosystem from internal, external, direct, and indirect directions and causalities (Obura and Grimsditch, 2009). Primarily, a steady rise in sea surface temperature has led to substantial damage through coral bleaching. According to the 1998 bleaching event alone, approximately 16% of global reefs perished, some losing 50-90% of coral cover (Wilkinson, 2000). Mass bleaching events have occurred throughout the years, even as recently as 2020, as reported in the "Status of Coral Reefs of the World: 2020" by the Global Coral Reef Monitoring Network (GCRMN, 2022). Further degradation is expected to continue annually even under ideal climate projections (Hoegh-Guldberg, 1999). Crucially, the factors driving coral bleaching have far-reaching and non-linear consequences ecologically, economically, and socially. The coral loss and resulting changes to habitat interactions have further importance on the biodiversity and abundance within those reefs (Pratchett et. al., 2011).

A previous study conducted on Misali's coral bleaching percentage in 2019, estimated that 63.4% of corals (n=843) presented significant signs (>5% of surface area) of bleaching (Kulick, 2019). The author of the paper concluded that this was likely due to environmental factors given that fishing practices were equally extensive in both locations. Furthermore, the study concluded that temperature was a driving factor in the coral bleaching percentage given the exposure to heat, sunlight, and air during the April 21st spring low tide event. While the paper focused solely on the bleaching percent coverage, this study helped further identify the causal relationship between temperature, the reef, and its fish inhabitants.

In another research study, the authors described a drastic dissociation between fish length and abundance in the two different extraction and non-extraction zones (Daniels et al., 2003). Daniels et. al found a “significantly lower abundance for Holocentridae […] exceeding warning thresholds.” The authors attributed this disparity to four interdependent causes: target species fishing, unintentional bycatch, habitat dependence, and effectiveness of the non-extraction zone. While all four express valid and essential factors, the third factor is particularly relevant, as this study sought to further specify the impact coral habitat loss due to temperature, has on fish population dynamics.

Thus, this study explores the relationship and effects of coral bleaching on the diversity of fishes in response to rising temperatures on Misali Island in Zanzibar, Tanzania. In doing so, this study has the potential to identify anthropogenic threats and coral reef ecosystem resiliency in order to inform future conservation efforts of Misali’s reefs and beyond.

4.0 Background

4.1 Coral Reefs as Ecosystems

Beyond their beauty and vibrancy, coral reefs are an essential part of biodiversity, housing nearly a quarter of all marine species despite covering only 1% of the planet (Obura and Grimsditch, 2009). Considered to be marine biodiversity hotspots, coral reef ecosystems are critical nurseries, breeding grounds, and habitats, offering an array of resources to oceanic species. Their ecological contributions are abounding, and offer protection for not just the species within them, but also the coastal communities around them.

Found in warm, shallow, tropical waters, coral reefs are constructed from the unique symbiotic relationship between a polyp (phylum Cnidaria, class Anthozoa) and algal zooxanthellae (National Geographic, 2019). The coral polyp is responsible for stability and nutrients by way of suspension-feeding, while the zooxanthellae's photosynthetic properties provide energy shared through their mutualism (West and Salm, 2003). The attachment begins as a free-floating polyp secures itself to a hard substrate associated with zooxanthellae, secreting CaCO3, and then divides and multiplies by means of binary fission. The resulting collective colonies function as one complex organism, later forming a coral matrix known as a reef (National Geographic, 2019).

The subsequent diversification of the marine environment facilitates the onset of niche micro-differentiation and resource partitioning of contemporaneous benthic species. In doing so, reefs support higher levels of coexistence by lessoning interspecies competition. In effect, coral reefs sustain superior levels of biodiversity and abundance that are inconsistent with the expectations based on the area alone (Obura and Grimsditch, 2009; National Geographic, 2019). This is all the more crucial given the warm, shallow waters they often inhabit are oligotrophic and lack substantial nutrients (National Geographic, 2019). However, the addition of primary production by the symbiotic zooxanthellae supports a diverse and abundant environment.

4.2 Coral Reef Threats and Response

As a direct consequence of anthropogenic CO_2 emissions, sea surface temperatures are steadily increasing, and with it, reef ecosystem degradation (Deser et al., 2010). It is estimated that by 2050, all reefs in the Indian and South Pacific Oceans (as considered in Meissner's study) will endure extreme heat stress, thereby making this study and others, imperative (Meissner, 2012). When under such heat stress, the coral partnership described above endures coral bleaching: the process in which the zooxanthellae release the algae causing a "bleached" appearance and the eventual death of the reef and inhospitable habitat (Brown, 1997). As reef ecosystems decline, the species dependent upon its resources will be forced out, causing cascading disarray across trophic levels.

According to the paper "Changes in Biodiversity and Functioning of Reef Fish Assemblages following Coral Bleaching and Coral Loss," coral loss greater than 60% consistently led to declines in fish diversity (Pratchett et. al., 2011). Furthermore, most fish species saw an exponential decline following a mass disturbance event that exceeded 10% of coral loss. While Pratchett et. al. defined coral reef loss as any natural or anthropogenically-caused damage, their research is further indicative of trends this study establishes when assessing temperature-caused coral loss.

These results were similarly mirrored in the long-term study conducted in Papua New Guinea (Jones, 2004). Interestingly, however, Jones' study saw the same trend reversed, suggesting a parallel relationship between coral health and fish diversity. Research depicted rapid degeneration in coral cover following a drop in fish biodiversity. During the research duration, there was a 75% decrease in reef fish abundance which was then followed by a 50% decrease in healthy coral cover. While the inverse of the previous study, Jones' research emphasizes the causal relationship and interdependency both variables share. This proves valuable going forth, as this study assesses the relationship between all variables involved, whilst acknowledging that causality may be flipped.

In a study conducted by Grimsditch et. al., East African reefs have been exposed to higher levels of heat stress compared to other reefs in the Indian Ocean (Grimsditch et. al., 2017). This study demonstrates an important pattern by showing that levels of heat stress directly influence the coral's resiliency and fish abundance. Specifically, research showed that "stress-tolerant" coral genera were more prominent in environments with high fish populations. Furthermore, Grimsditch et. al. supports the interconnected nature between the three research variables explored by this paper.

4.3 Implications for Reef Resiliency

The term Climate Change caries a doomful connotation, yet, it drives home the importance of research efforts as described above to conserve such a vital habitat. As one of the most vulnerable ecosystems to climate change, coral reefs are reliant on stability (Pratchett et. al., 2011). Specific to this study, corals rely on temperature consistency, as bleaching can occur if oceanic temperatures exceed the norm by even 1.0˚C. In turn, coral reef fishes are also reliant on the reef's stability, thereby making the temperature a vital controlling factor. The corallivorous fish, in turn, promote ecosystem resiliency by regulating algae. However, if temperature changes disrupt the fishes' behavior, coral health can no longer be maintained. Furthermore, if inversed, the relationship between reef fishes and coral health still traces back to the importance of stable temperatures. While much is understood about coral bleaching independently, little is known about its intersection with fish assemblage and rising temperatures. Thus, it is imperative that this study examine the threat of coral decline on fish biodiversity in response to temperature and how such a loss may impact reef ecosystem resiliency against Climate Change.

4.4 Study Area

Misali Island is located at 5°15'S 39°36' E, approximately 10km off the west coast of Pemba Island in the Zanzibar Archipelago, Tanzania (Levine, 2015). Misali is uniquely positioned adjacent to the Pemba Channel which reaches a maximum depth of 800m. The steep bathymetry causes upwelling, spilling cold and nutrient-rich water into the surrounding fringing reefs. This upwelling increases biological productivity and serves as a buffer against heat stress. Misali's reefs are among the healthiest in the archipelago in large part to their protected status under Pemba Channel Marine Conservation Area (PECCA) (Kulick, 2019). As per PECCA's zonation, the island's reefs are divided into a non-extraction zone on the western side adjacent to the Pemba Channel, and an extraction zone on the northeast side adjacent to a shallow channel separating Misali from Pemba. Additionally, its seclusion from urban and agrarian activities further protects the reef from anthropogenic threats such as runoff. Named as a biodiversity hotspot, Misali's reefs represent 80% of all coral species found in East Africa, thereby adding to its ecological productivity, fisheries success, and tourism appeal (Jones, 2017). A survey conducted in 2017 estimated fish abundance in the extraction zone with over 200 species observed. The study suggested that Misali's fish assemblages in the extraction zone only depicted a fraction of the estimated diversity in the non-extraction zone. As home to one of the highest abundances of fish, including commercially and ecologically important species, Misali's reefs remain a crucial habitat for future conservation efforts. Other reefs across the Zanzibar Archipelago experience greater anthropogenic influence, but similar bleaching alerts and tides (Kulick, 2019). Thus, Misali's coral reefs are indicative of reef health in Zanzibar and can serve as a model for the greater East African coast.

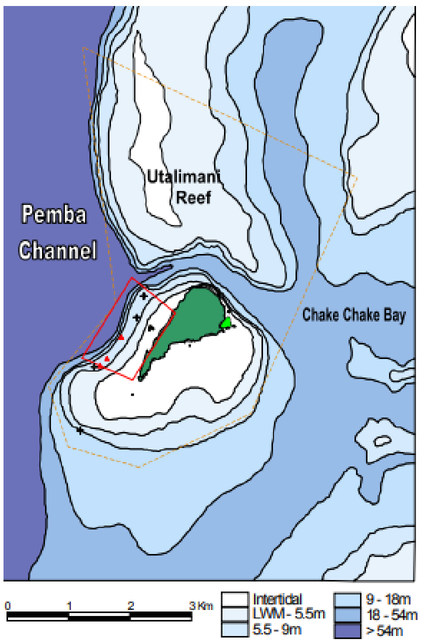


Figure 1. Map illustrates the old Non-Extraction Zone (solid red line) and MIMCA protection zone (dotted yellow line) and proximity of the western reefs to the Pemba Channel (image from Richmond and Mohammed, 2001:9)

Figure 2. Map of Transects (n=30) on Misali Island. Yellow points mark the boundaries of the Non-Extraction Zone, yellow line shows the path of transects when connected. Green points mark the boundaries of the Extraction Zone, green line shows the path of transects when connected (Image rendered via Google Earth).

5.0 Methods

5.1 Data Collection

5.1.1 Transects

In an effort to understand the threat of temperature on coral reef habitats and fish diversity, this study utilized parallel 25m linear transects (n=30) in two different zones along Misali's reefs for a duration of 22 days (Figure 2). The sample size was divided evenly between the two sites (NEZ=15, EZ=15). Specifically, the zones were determined by the temperature and depth disparities created by the western side's channel. When contrasting the two fringing reef sites, the northeast and western zones were selected based on their similar reef topography and fishing allowances to minimize error due to environmental variation. Transects were laid using a 50m tape measure for minimal environmental impact, at 25m intervals while marking the GPS coordinates. Additionally, swimming safety was carefully assessed accordingly to the Misali rangers' judgment. In the event of unsafe swimming conditions due to the proximity of the strong currents of the Pemba Channel, an alternate site was selected based on a shallower depth, yet similar temperature and reef settings. Swimming safety was further accounted for by adding boat, ranger, and secondary investigator assistance during in-situ analysis. Once swimming conditions were established, the swim time was closely considered to ensure consistency across transects and zones to minimize bias in the data.

5.1.2 Environmental Parameters

Once transects were set, the principal investigator measured the environmental parameters at the surface to allow the fish communities to reacclimatize to the reef and minimize human-influenced behavior and error. Such parameters included measuring sea surface temperature (SST), deep water temperature (DWT), depth, turbidity, tidal stage, time of day, and weather conditions. SST was measured using a thermometer submerged a few centimeters below the surface. DWT was measured using the same thermometer at a depth of the highest bathymetric point of coral along the transect. Depth was visually estimated; however, later confirmed by the software, Ocean Data View (ODV) once coordinates were marked. Depth is an important variable in correlating temperature with the reef health indicators studied, as it is assumed temperature decreases as depth increases. The turbidity was initially measured using a Secchi Disk in an effort to further correlate the light availability with the temperature findings. However, once it became clear that the depth was too shallow to facilitate accurate Secchi Disk measurements, turbidity was considered 0 unless visually noted otherwise. The tidal stage also informed factors relating to temperature, depth, and sun exposure. Additionally, the time of day and weather conditions helped eliminate other environmental variables from conclusions regarding temperature.

5.1.3 Fish Survey

Following preliminary measurements, the principal investigator swam the length of the transect and counted the number of fish species using a pre-made ID guide and datasheet (Appendix). The principal investigator used an underwater video camera (Kodak EIS) for post-swim analysis to ensure all species were correctly identified and counted. Additionally, the video provided size comparisons between species and reef sites.

5.1.4 Coral Survey

Following the fish survey, the principal investigator swam the transect back to its origin point while recording reef rugosity and coral bleaching percent coverage. Reef rugosity was quantified by a visual scale from 1-5 (1: flat to no corals, 5: well-established, complex reef). Coral bleaching percent cover was also visually estimated on a percentage scale (0-5%, 6-25%, 26-50%, 51-75%, 76-95%, 96-100%). Additional observations were recorded, including the presence of Crown-of-Thorn Starfish, pathogens, anchor damage, or other abnormalities that may skew the data.

5.2 Data Analysis

Previous studies regarding coral reef health and fish diversity have frequently been published separately and are rarely considered together. Therefore this study used a combination of their respective statistical approaches. While previous Misali research was used for general comparisons of reef health and fish diversity, given the lesser sampling and inconsistency in overlapping sites, the statistical methods used are independent of their respective results.

Data management included the accumulation of reef health measurements and fish diversity and abundance in the printed field guides (Appendix). Once organized in a replicate digital copy via Excel, data were analyzed using a series of T-Tests: Two-Sample Assuming Equal Variances with an alpha value of 0.05. Graphs were rendered accordingly with linear regression trend lines and R^2 values displayed for further visual analysis and statistical significance.

6.0 Results

6.1 Temperature and Environmental Parameters

Across all 30 transects, the temperature was measured at both the surface (SST) and highest bathymetric feature (DWT). Between the Extraction (EZ) and Non-Extraction (NEZ) zones, both the SST and DWT show statistical significance ($p<0.05$; $p=1.54E-6$, $p=5.87E-7$ respectively), with the NEZ demonstrating lower temperature measurements than the EZ. The average NEZ SST was 26.4℃ and DWT was 26.2℃, whereas the average EZ SST was 27.53℃ and DWT was 27.4℃.

The maximum tidal height reached throughout the 22-day duration was 4.1m above sea level, and the minimum was -0.2m below sea level. Transects were conducted at low tide 63.3% (n=19), mid-low tide 23.3% (n=7), mid-high tide 6.67% (n=2), and high tide 6.67% (n=2) of the time. Depth was considered in tandem with tidal height. The average depth of all 30 transects was 2.78m, with a minimum of 1.5m and a maximum of 5.5m in correspondence with their respective tidal heights.

As previously noted, turbidity was initially measured using a Secchi Disk; however, after determining the water's turbidity to be too minimal to read on the Secchi Disk apparatus, the turbidity was considered an environmental constant. There were two dates of note in which visibility was slightly more turbid given prior storms; however, once again the measurement was too minimal to be accurately measured by the Secchi Disk.

6.2 Fish Diversity and Abundance

Using the pre-prepared ID guide and datasheet of the 28 families chosen, 24 fish families were observed (Appendix). The four unobserved families, Monacanthidae, Scorpaenidae, Apogonidae, and Monodactylidae, were omitted from the statistical analysis. It is also important to note that the four families, Syngnathidae, Gerreidae, Gobiidae, and Blenniidae, had minimal species representation ($n<4$). The total fish abundance was 2799 (NEZ n=1894; EZ n=905) (Figure 4; Figure 5; Figure 6). Amongst all families observed, Acanthuridae, Pomacentridae, Chaetodontidae, Labridae, and Haemulidae showed statistically significant higher abundances in the NEZ than in the EZ (p<0.05; p=0.0047, p=0.0338, p=0.0023, p=0.0327, p=0.0332 respectively).

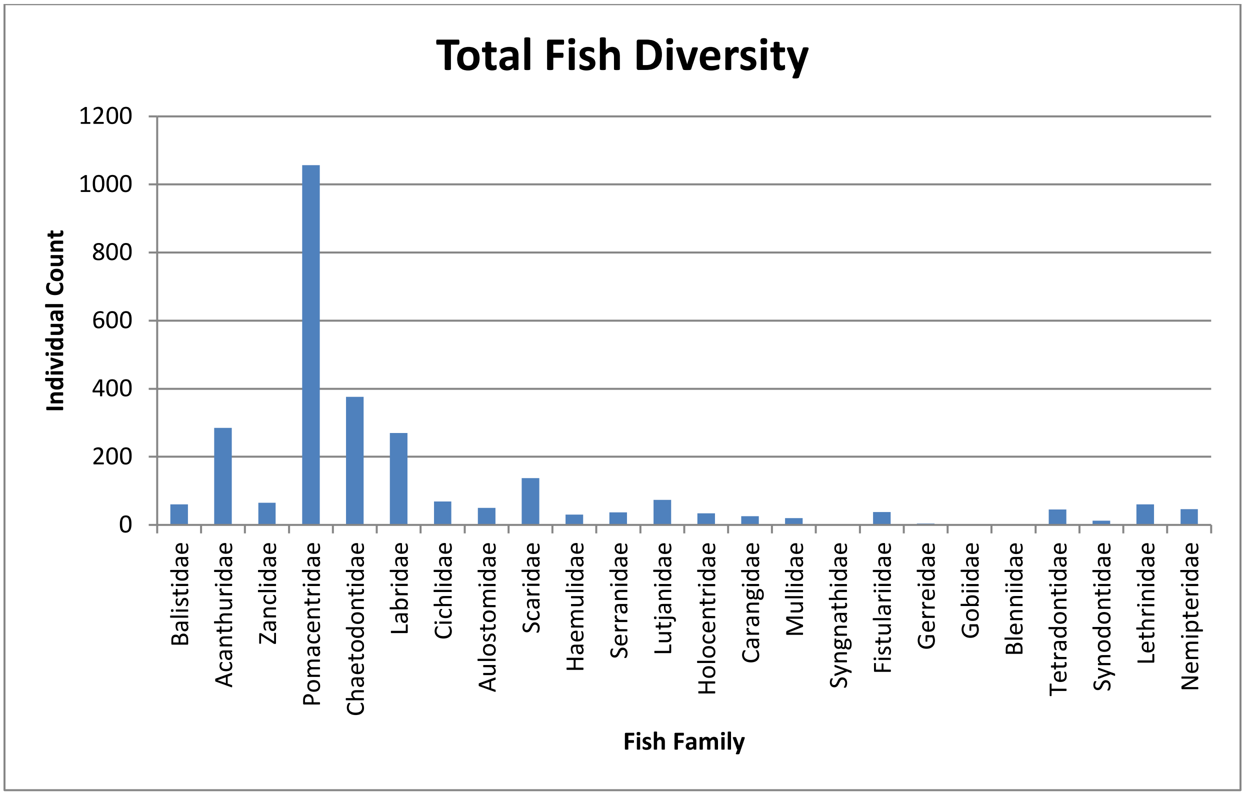


Figure 4. Fish family diversity, abundance, and composition across all 30 transects surveyed at Misali Island (n=2799).

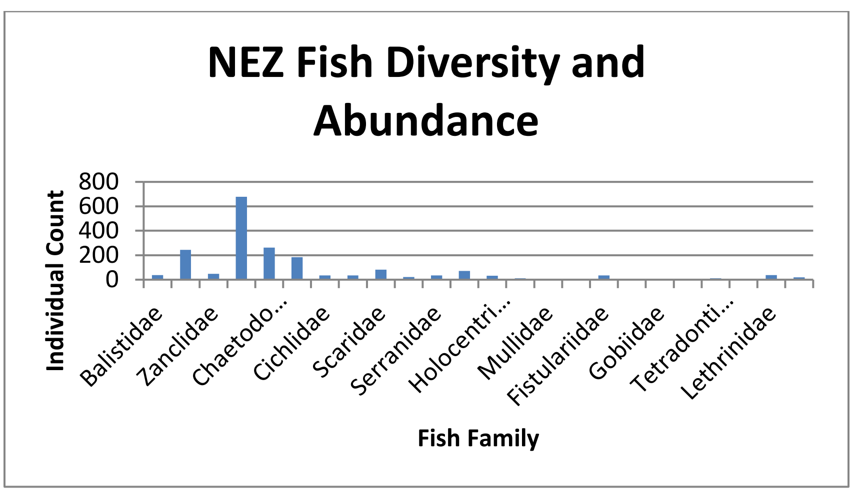


Figure 5. Fish family diversity, abundance, and composition across the 15 transects surveyed within the Non-Extraction Zone (NEZ) at Misali Island (n=1894).

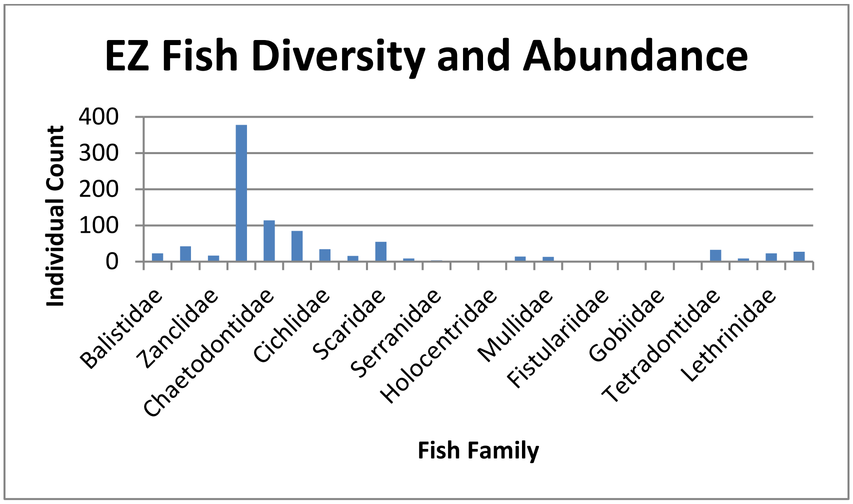


Figure 6. Fish family diversity, abundance, and composition across the 15 transects surveyed within the Extraction Zone (NEZ) at Misali Island (n=905).

6.3 Keystone and Indicator Species

6.3.1 Balistidae

The total abundance of Balistidae species counted within the NEZ and EZ is 60 (n=37; n=23, respectively), representing 2.14% of all observed fish. Balistidae showed no statistical significance between the two zones ($p>0.05$).

6.3.2 Pomacentridae

The total abundance of Pomacentridae species counted within the NEZ and EZ is 1057 (n=679; n=378, respectively), representing 37.76% of all observed fish. The Pomacentridae family is statistically significant, with a higher abundance in the NEZ than in the EZ ($p<0.05$, $p=0.0338$)

6.3.3 Chaetodontidae

The total abundance of Chaetodontidae species counted within the NEZ and EZ is 376 (n=262; n=114, respectively), representing 213.43% of all observed fish. The Chaetodontidae family is statistically significant, with a higher abundance in the NEZ than in the EZ ($p<0.05$, $p=0.0023$)

6.3.4 Scaridae

The total abundance of Scaridae species counted within the NEZ and EZ is 137 (n=82; n=55, respectively), representing 4.89% of all observed fish. Scaridae showed no statistical significance between the two zones ($p>0.05$).

6.4 Coral Reef Rugosity and Bleaching

6.4.1 Rugosity

Coral reef rugosity differed drastically between the Non-Extraction and Extraction zones, showing statistical significance (Figure 7). Despite an accumulated average of 3.33, the NEZ's average is an entire point higher, with a average rugosity of 3.83.

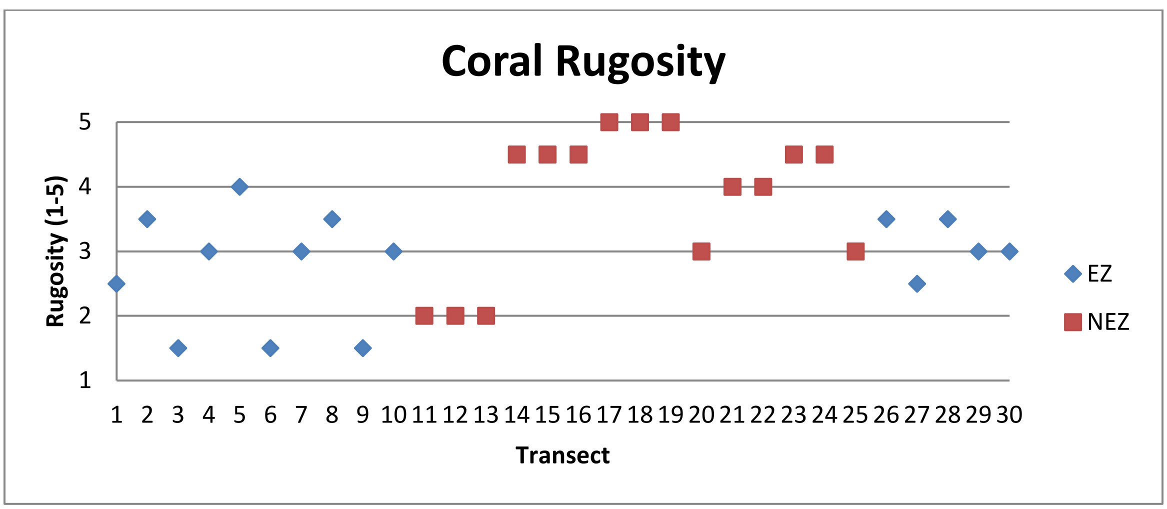


Figure 7. Coral reef rugosity on a scale of 1-5 (1 being a sparse reef, 5 being a fully developed reef) observed in the Extraction Zone (blue markers) and Non-Extraction Zone (red markers)

6.4.2 Bleaching

Coral reef bleaching was present at all transects surveyed, with an average percent cover of 8.53%, a maximum of 15%, and a minimum of 5%. Though there was no statistical significance between coral bleaching percent cover in the Non-Extraction and Extraction zones, the modes described the most common bleaching percentage in the NEZ and EZ to be 5% (n=8, n=8).

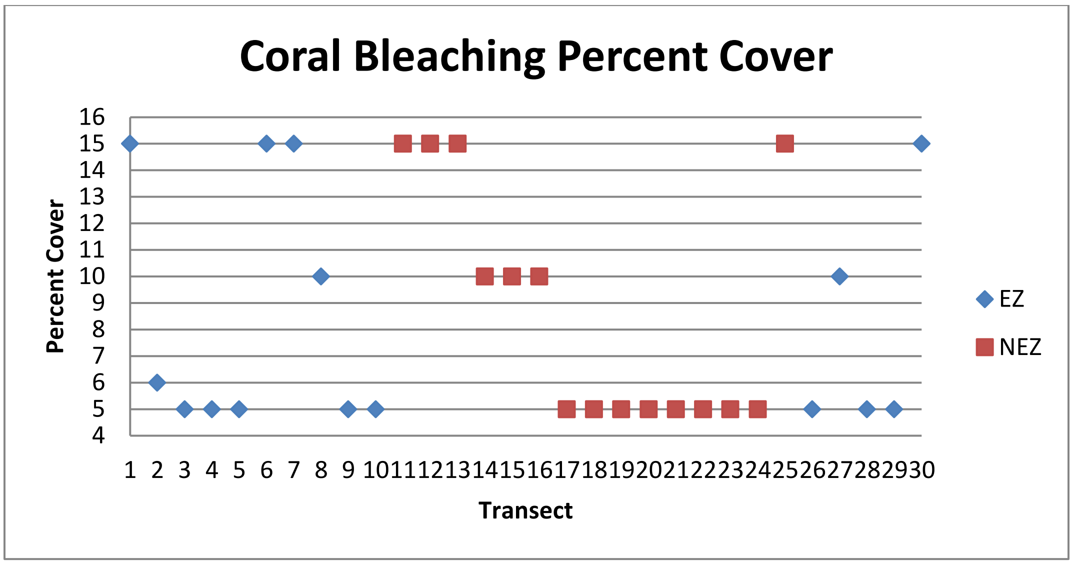


Figure 8. Coral bleaching percent cover observed in the Extraction Zone (blue markers) and Non-Extraction Zone (red markers)

6.4.3 Rugosity, Bleaching, and Fish Abundance Relationships

Coral reef rugosity and bleaching were overlaid in order to establish any trends and rule out extraneous variables that impede a causal relationship between reef health and fish abundance and diversity (Figure 9; Figure 10). The relationship between coral reef rugosity and bleaching in both the EZ and NEZ holds no statistical significance. However, the visual trends shown in the NEZ appear to demonstrate an inverse relationship given that as bleaching percent cover decreases, rugosity increases, and vice versa (Figure 10).

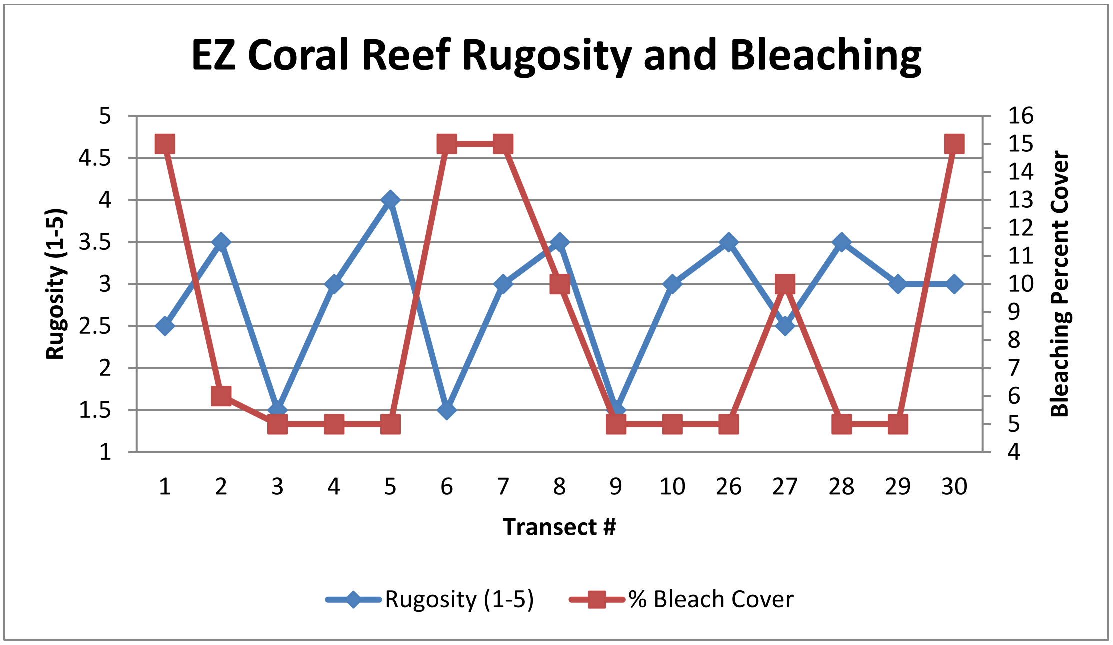


Figure 9. Coral reef rugosity (primary y-axis) and bleaching percent cover (secondary y-axis) observed in the Extraction Zone.

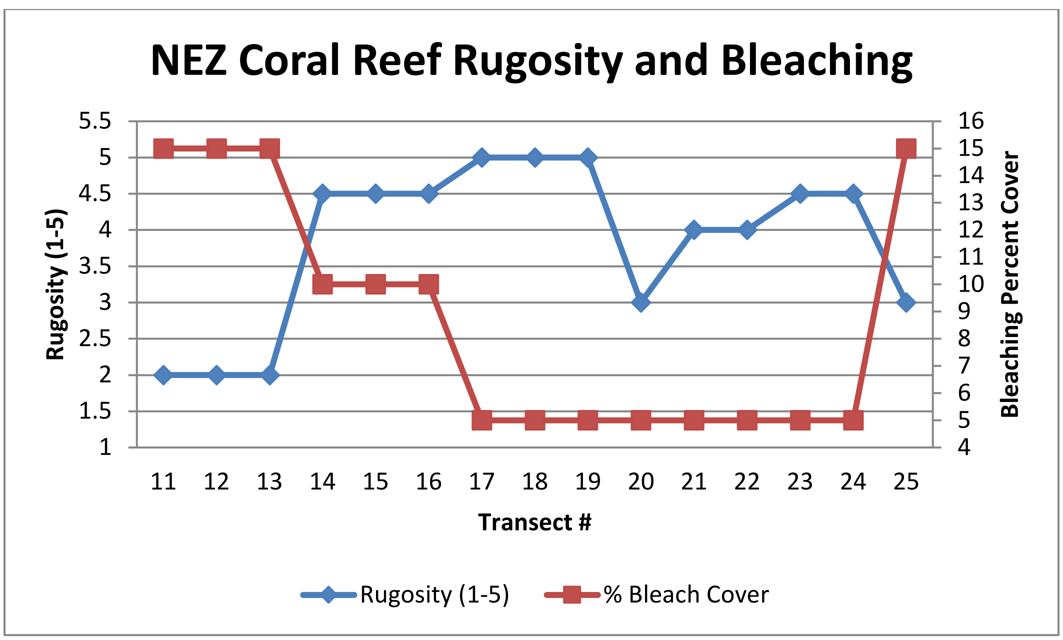


Figure 10. Coral reef rugosity (primary y-axis) and bleaching percent cover (secondary y-axis) observed in the Non-Extraction Zone.

According to Figure 11, reef rugosity and fish abundance are statistically significant when sorted from lowest to highest rugosity levels given the linear regression R^2 values (R^2 =

0.970; $R^2 = 0.5$) (Figure 11). Figure 12 further confirms the significance within the NEZ; however, EZ is insignificant, likely due to outliers in transects 2, 7, 26 (Figure 12; Figure 13).

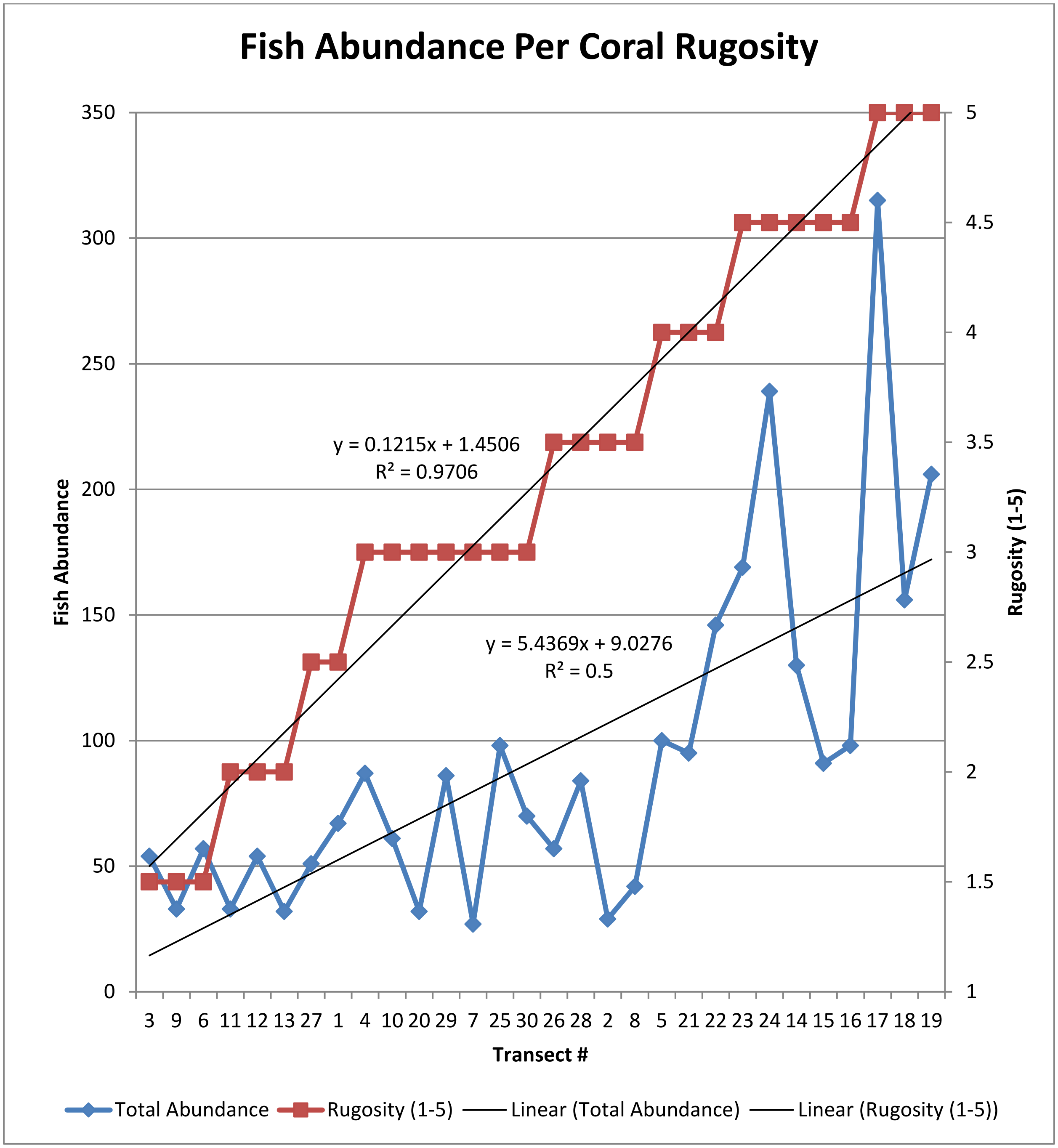
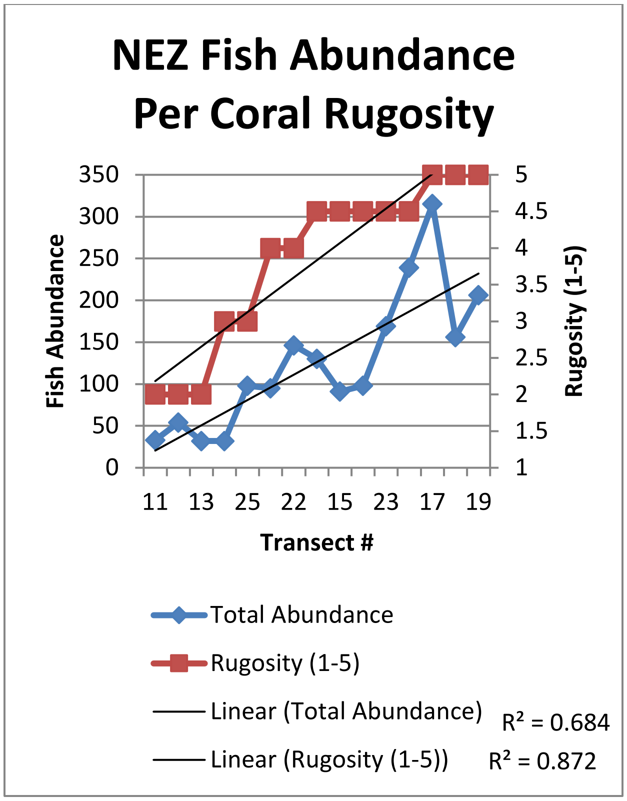


Figure 11. Fish Abundance (primary y-axis) and coral reef rugosity (secondary y-axis) observed in both the Non-Extraction and Extraction Zone. The transect number corresponds to the data when sorted from lowest to highest rugosity.



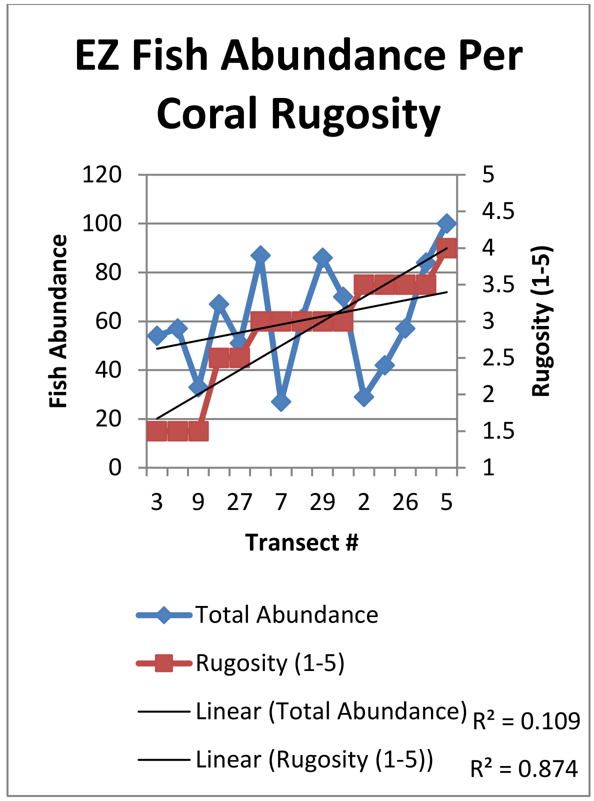


Figure 12. Fish Abundance (primary y-axis) and coral reef rugosity (secondary y-axis) observed in the Non-Extraction Zone. The transect number corresponds to the data when sorted from lowest to highest rugosity.

Figure 13. Fish Abundance (primary y-axis) and coral reef rugosity (secondary y-axis) observed in the Extraction Zone. The transect number corresponds to the data when sorted from lowest to highest rugosity.

When comparing coral bleaching percent cover and fish abundance, there appears to be little statistical significance according to the linear regressions (transects sorted from lowest to highest coral bleaching percent cover) depicted in Figure 14 ($R^2 = 0.797$; $R^2 = 0.117$) likely due to outliers in transects 3, 9, and 20 and smaller sample size (n=30) (Figure 14). However, the visual trend depicts an inverse relationship, similar to that of Figure 10's relationship between rugosity and bleaching. The inverse correlation between coral bleaching and fish abundance is further supported in the NEZ and EZ independent graphs, though the R^2 values for abundance linear regression are insignificant for the reasons expressed above (Figure 15; Figure 16).

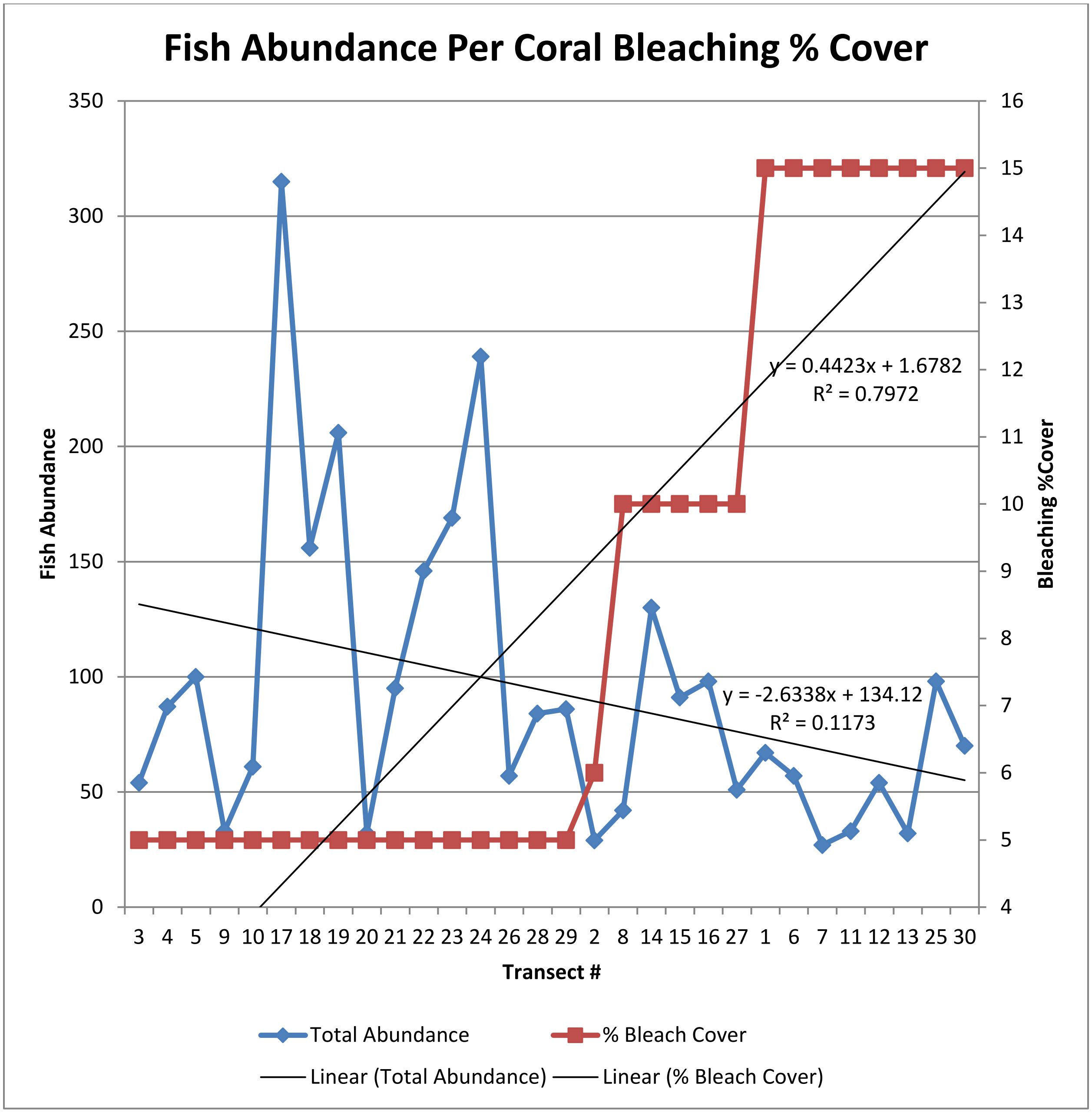


Figure 14. Fish Abundance (primary y-axis) and coral bleaching percent cover (secondary y-axis) observed in both the Non-Extraction and Extraction Zone. The transect number corresponds to the data when sorted from lowest to highest coral bleaching percent cover.

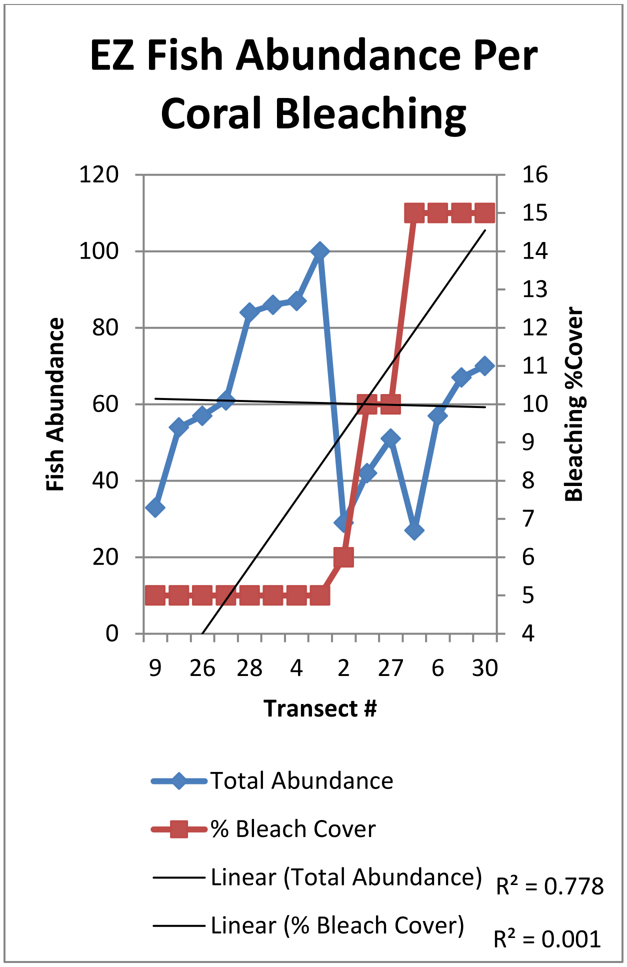


Figure 15. Fish Abundance (primary y-axis) and coral bleaching percent cover (secondary y-axis) observed in the Extraction Zone. The transect number corresponds to the data when sorted from lowest to highest coral bleaching percent cover.

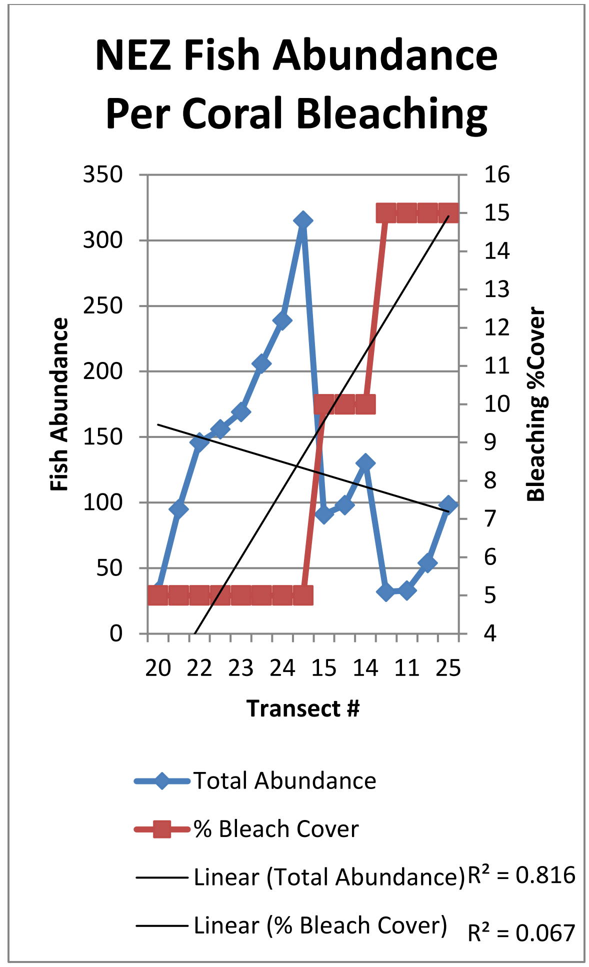


Figure 16. Fish Abundance (primary y-axis) and coral bleaching percent cover (secondary y-axis) observed in the Non-Extraction Zone. The transect number corresponds to the data when sorted from lowest to highest coral bleaching percent cover.

7.0 Discussion

7.1 Temperature and Environmental Parameters

Previous research estimated the 63.4% of corals in Misali showed significant bleaching (Kulick, 2019). Given the equivalent levels of fishing observed between the two zones and the NEZ's proximity to cold upwelling from the Pemba Channel, the author concluded that bleaching was attributed to temperature-driven environmental factors. Their conclusions mirror the results of this paper given the statistical significance between SST and DWT in the NEZ and EZ zones. It is especially noteworthy considering coral's sensitivity to temperature. Thus, even though the difference in averages was minimal, bleaching can occur if oceanic temperatures exceed the norm by even 1.0˚C (Pratchett et. al., 2011). It is all the more important given that very little is known about changes in fish assemblages and their physiological response to heat stress. While there was no significant difference between SST and DWT temperature measurements likely due to the shallow depth of transects, future research should carefully consider this distinction if expanded to deeper reefs. However, it is also worth acknowledging that due to the limited nature of this study, seasonality and natural temperature variations could not be observed as influencing factors. Despite the lack of long-term temperature monitoring, the statistical significance between the two zones provides satisfactory evidence that temperature is a driving force in reef health.

To further support temperature's impact on reef health, turbidity was considered an environmental constant as a result of the shallowness and distance from pollutants and anthropogenic emissions. Though the measurements were too minimal to be accurately measured on the Secchi Disk, the lack of turbid conditions preventing light penetration further emphasized the potential for temperature-related changes such as bleaching. When considered in tandem with turbidity, the frequency of shallow depths and low tides offers additional support to this claim.

7.2 Fish Diversity and Abundance

Within the two sites studied, a total of 2799 fishes were observed across 24 different families. According to previous species accumulation predictions for Misali, this number likely represents a fraction of the expected population given limited sampling (Jones, 2019). While there was no statistically significant difference between the total abundances in the NEZ and EZ, the families Acanthuridae, Pomacentridae, Chaetodontidae, Labridae, and Haemulidae showed statistically significant higher abundances in the NEZ than in the EZ. The lack of evidence to support the expectation that the NEZ would contain a higher abundance given its protection supports the claim that enforcement and community engagement have markedly decreased (Levine, 2015). Additionally, active fishing and Dema traps were observed in both zones every time a transect was conducted during this study. Due to the fraught issues of NEZ regulation, fishing pressures appear equivalent in both zones and therefore can be excluded when considering the causation of fish abundance disparities. It should also be noted that depth strongly influences fish assemblages, and therefore, future studies should be expanded to greater depths for a wider survey of fish populations in Misali (Jennings et al.,1996).

7.3 Keystone and Indicator Species

Among all 24 families considered in this study, four: Balistidae, Pomacentridae, Chaetodontidae, and Scaridae, represent indicator and keystone species, making their presence among the others significant considering their role in maintaining reef health and dynamics.

Balistidae and Scaridae species, commonly known as Triggerfish and Parrotfish respectively, are vital corallivores; however, were statistically insignificant between the NEZ and EZ. However, the Pomacentridae and Chaetodontidae species, commonly named Damselfish and Butterflyfish, are statistically significant, with a higher abundance in the NEZ than in the EZ. Additionally, Pomacentridae represent 37.76% of all observed fish, making it the largest family composition among all 24 families. Previous studies surveyed from 1992 to 2017 showed historically comparable levels of abundance for all four families above (Jones, 2019). However, the historical trends are showing a gradual decrease in keystone, predatory, and reef indicator species. While statistical comparisons cannot be drawn between the historic levels due to inconsistent sampling and dissimilar methods, it can be concluded that due to only two of the four families showing statistical significance, this study suggests a possible decrease in reef health indicator species and keystone species as a potential outcome of failing reef resilience.

7.4 Coral Reef Rugosity and Bleaching

Reef health, for the purposes of this study, is defined to be high levels of rugosity, low levels of coral bleaching, and appropriate levels of fish diversity and abundance as supported by the reef's carrying capacity. In an effort to identify reef health in response to the two different temperatures in the NEZ and EZ, Rugosity, Bleaching, and Fish Abundance relationships were analyzed to support the hypotheses made above.

Coral reef rugosity as shown in Figure 7 varies significantly in the Non-Extraction and Extraction zones, with a higher level of rugosity expressed in the NEZ (Figure 7). In contrast, coral bleaching demonstrated no statistical significance between the zones. However, when overlaid one another, the two visually depicted the trend that as coral bleaching increases, rugosity decreases. This result confirms the expectation that coral bleaching damages reef rugosity, and establishes a foundation for conclusions about fish abundance and reef health.

When comparing coral reef rugosity with fish abundance, there appears to be statistical significance according to the linear regressions (transects sorted from lowest to highest rugosity) depicted in Figure 11, corroborating the graph's visual trend (Figure 11). The positive correlation between rugosity and fish abundance is further supported in the NEZ independent graph, though the EZ displays no significance (Figure 12; Figure 13). The results support the expectation that rugosity and fish abundance are directly related in that as one increases, the other follows. In essence, healthier, abundant reefs are likely to carry more fish species as seen in the Non-Extraction Zone versus in the less healthy (by standards set by this study) Extraction Zone.

While the comparison between coral bleaching percent cover and fish abundance yielded little statistical significance, the visual trend shown in Figure 14 demonstrates an inverse relationship, similar to that of Figure 10's relationship between rugosity and bleaching. When considered independently, Figures 15 and 16 mirrors the pattern, further supporting the understanding that as coral bleaching increases, fish abundance decreases. This finding is in line with the definitions of reef health above. Coral bleaching events have been shown to leave lag effects, adversely impacting reef fish assemblages for years; however, dead coral structures can remain intact and continue to house fish communities, impacting the reef's health timeline (Muhando and Mohammed, 2002). Given the most recent bleaching event was in 2020, it is likely that results may not fully represent the extent of coral bleaching's impact on fish diversity and abundance, particularly corallivorous fish. Thus it is recommended that future research be conducted over a large scale of time to observe any gradual changes in fish populations. That being said, trends in this study still demonstrate a significant link between reef health, fish composition, and temperature-driven consequences.

8.0 Conclusion

This study's objective was to assess the role temperature has on the intertwined variables dictating reef health on Misali Island, Tanzania. In doing so, rugosity, coral bleaching percent cover, and fish composition were analyzed in their respective temperature zones. The results not only supported the assertion that the three variables above shared an important relationship with one another but further indicated that reef health was stronger in the NEZ cooler waters than in the EZ warmer waters. While it is unclear if it is temperature-driven bleaching leads to a decrease in fish composition, or if it is temperature-driven decreases in fish that lead to coral reef degradation or both, what is clear is that the variables have a significant relationship between one another and must be considered carefully in the coming years of anthropogenic influence. While Misali is only representative of a small area of reefs, it is the author's hope that the results of this study help inform future management and conservation efforts to improve reef and fish resiliency in the face of rising global temperatures.

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9.0 Recommendations

The importance of reef health cannot be overstated as reef ecosystems decline, the deterioration of trophic interactions will cascade into coastal livelihoods, and eventually disrupt the global biological, economic, and social balance (Kulick, 2019). Thus, this study sought to identify reef health and fish assemblage in regard to two different temperature zones in hopes of understanding temperature-driven consequences for future conservation efforts. While the study was conducted as thoroughly as permitted by the limited time and resources available; however, future studies should expand geographically, by covering longer transects in deeper reefs using SCUBA and other underwater monitoring devices. Increasing transect coverage will yield higher sample sizes, thereby minimizing standard error. Additionally, it is recommended that future research span across a variety of seasons while continuously logging temperature to establish natural variations. Future researchers are encouraged to build upon the variables measured in this study, particularly by identifying the coral genus and growth type to better identify stress-tolerant genera for potential reef restoration projects. To mitigate heat stress on corals and fish alike, reef health should continue to be monitored on a larger scale and duration. Additional factors outside of this study's purview should also be considered to gain a broader understating of reef health and improve conservation responses.

In addition to the aims of this study, it is crucial to engage other factors controlling reef ecosystem health including the reef's proximity to human habitation, boat traffic, evidence of fishing, over-exploitation of recourses, unsustainable tourism practices, human detritus, and the presence or absence of indicator species. Studies have shown that noise pollution from increased boat traffic severely impacts the settlement of fish and coral larvae alike, thereby disrupting coral reef population dynamics and structures (Holles et al., 2013). Another primary contributor to reef decline that is not within this study's parameters is frequent boat anchorage, as the physical damage caused; impacts future coral growth and fishes' migratory and reproductive patterns (Flynn & Forrester, 2019). While Misali is uniquely free of many of these factors, it should be noted that many reefs in the Zanzibar Archipelagos are inundated by urban impacts, nutrient pollution, wastewater contamination, and plastic pollution (Carlson et al., 2019). Thus, this study serves as an indicator to gauge reef ecosystem resilience in both healthy, protected reefs, and unhealthy, unprotected reefs. With the increase in tourism development and urban investments on the horizon, conservation and management plans for Zanzibar's reefs are necessary to help mitigate anthropogenic impacts (Johnstone et. al., 1998).

Several models have predicted increased coral bleaching as sea surface temperatures continue to rise globally, making conservation efforts all the more vital. This study further indicates a need to focus on Misali as a PECCA-protected reef. In doing so, it is recommended to increase ranger presence and adequate resources to support the level of patrolling required across the 1000km^2 areas, particularly in the Non-Extraction Zone. Additionally, to ensure NEZ enforcement, it may be beneficial to place substantial markers demarcating the NEZ boundary. To further protect the shallow reefs studied, mooring buoys should be anchored around the ranger station and fisherman camps in such a way that mitigates anchor damage to coral habitats. While these efforts help maintain the current state of reef health without interference, to prevent significant coral loss in future bleaching events, it is recommended that reef restoration projects such as farming stress-resistant and heat-tolerant species are implemented. While restoration projects such as these operate on a longer time scale, reef fish will have time to acclimate to the change in habitat. It is the hope that stress-resistant corals will thrive and indirectly benefit other reefs by dispersing through the strong currents in the Pemba Channel.

10.0 References

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11.0 Appendix

Date:		Transect #:		GPS:								
Family	**Balistidae**	**Acanthuridae**	**Zanclidae**	**Pomacentridae**	**Chaetodontidae**	**Labridae**	**Cichlidae**	**Aulostomidae**	**Scaridae**	**Monacanthidae**	**Haemulidae**	**Serranidae**
Common Names	Trigger Fish	Unicorn Fish, Surgeonfish, Tang	Moorish Idol	sergant fish, cromis, damsel, humbug, anemonefish, cowfish	Butterflyfish, Bannerfish	wrasse, coris	angelfish	trumpetfish	parrotfish	Filefish	grunter, sweetlips	grouper
Tally												
Notes:												
Family	**Lutjanidae**	**Holocentridae**	**Scorpaenidae**	**Carangidae**	**Mullidae**	**Syngnathidae**	**Fistulariidae**	**Gerreidae**	**Apogonidae**	**Gobiidae**	**Blenniidae**	**Monodactylidae**
Common Names	snapper	Squirrelfish, soldierfish	lionfish, scorpionfish, stonefish	ruddlerfish, runner, trevally	goatfish	pipefish	cornet fish	silver biddy	cardinal	goby	fangblenny	silver moony
Tally												
Notes:												

Date:		Transect #:		GPS:		Time:	
Measurement:	**Rugosity (1-5)**	**% Bleach Cover**	**Turbidity**	**SST**	**DWT**	**Tidal Stage**	**Depth**
Response:							
Notes:							