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An Assessment of Coral Bleaching near Misali Island, Tanzania

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Zanzibar Coastal Ecology and Natural Resource Management

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1.0 Acknowledgements

This study would not have been possible without the help, resources, and endless support of many people. I want to thank the rangers at Misali Island - Mohammed and Haji - for welcoming us to the island, supporting us during our study period, and making Misali feel like home. I would like to thank Dr. Richard Walz and Dr. Christopher Muhando for their academic support, guidance, and constructive feedback throughout this study. I would like to thank Said Omar and the rest of the SIT staff for making this study possible by organizing the logistics of our travel and stay at Misali Island. I would also like to thank Dr. Jennifer Hoeting for her statistics consultation and guidance on using R programming for data analysis. Last but not least, I would thank the Misali Crew –Isabelle, Natalie, and Gabe – for making our time at Misali truly unforgettable.

2.0 Abstract

Coral bleaching and reef health were studied in fringing reefs around Misali Island, Tanzania. Over a 28-day period, 1,329 coral colonies were surveyed along 31 transects. For each colony, data was collected on growth form and bleaching severity. No significant differences in bleaching frequency or intensity were observed between the resource extraction and non-extraction zones protected under the Pemba Channel Marine Conservation Area (PECCA). Bleaching was observed to be extensive across all coral growth forms and was found to collectively increase over the study period in frequency and intensity. This study indicates the vulnerability of Misali coral reefs to bleaching and reef degradation and draws attention to the ecological instability caused by global change and anthropogenic impact.

Kiswahili

Kupauka kwa rangi asilia ya matumbawe pamoja na ubora wa kimazingira wa matumbawe yalifanyiwa utafiti katika miamba ya matumbawe katika kisiwa cha na Misali, Tanzania. Kwa kipindi kisichopungua siku 28, makundi ya aina za viumbe aina mbali mbali wanaoishi takribani, 1,329 makundi hayo ya matumbawe yalipimwa kwa kutumia transekti 31. Kwa kila koloni,programu ya kunakili takwimu zilitumiwa kuangalia uhai na kupauka wa rangi asilia. Hakuna tafauti mzunguko mkubwa wa rangi asilia ya matumbawe au viwango vilivyoonekana bainaya maeneo tengefu na maeneo yasio tengefu yanayohifadhiwa chini ya hifadhi ya PECCA. Upaukaji wa rangi asilia ulikuwa mkubwa katika maeneo ambayo matumbawe yanayokuwa, nakuoongezeka katika kipindi cha utafiti na kuonekana kwa kiwango kikubwa. utafiti huu unaonyesha hatari ya Matumbawe ya Misali kuendelea kupauka kwa kupoteza rangi yake ya asilia pamoja na kumomonyoka kwa matumbawe, na kutoa angalizo kuwa mifumo ya kiikologia inayosababishwa na hali ya tabia nchi na atahri za matendo ya wanadamu.

3.0 Introduction

Coral reefs are marine biodiversity hotspots which provide quality habitat, feeding, and breeding areas for fish and invertebrates and vital ecosystem services to human communities due to their structural complexity and high productivity (Obura and Grimsditch, 2009). However, such reefs are experiencing degradation and are falling increasingly under threat across the globe as rising temperatures, ocean acidification, and anthropogenic stressors produce widespread coral bleaching and mortality events (West and Salm, 2003). Over-fishing, resource extraction, and the associated physical damage caused by these activities are a major concern for the preservation of coral reef ecosystem integrity (Obura and Grimsditch, 2009). In this study, coral reef health and bleaching will be assessed in fringing reefs around Misali Island, Tanzania, East Africa.

Misali Island is important because it is a marine biodiversity hotspot in eastern Africa (Kertesz, 2000:7; Poonian, 2008). It serves as an indicator of the health and status of reefs across the Zanzibar Archipelago. The reefs at Misali are expected to be in better health than others in the archipelago due to its isolation from urban and agricultural run-off, its protection status under Pemba Channel Marine Conservation Area (PECCA), and the cool upwelling of water from the adjacent Pemba Channel, which serves as a buffer against heat stress. If reef health is poor at Misali, in general it can be expected to be worse in most other locations across the archipelago.

By studying reef health at Misali Island, and how coral health and bleaching intensity differ in zones under varying anthropogenic pressure, this study adds to the growing body of knowledge on the conditions influencing reef dynamics and the ecosystem services they provide to communities across the Zanzibar Archipelago. This study links bleaching intensity to environmental phenomena in the region, anthropogenic impacts, and inherent differences in the different morphologies of coral growth forms. By incorporating this framework into our understanding, this study has the potential to inform future management practices on how to improve reef resiliency and longevity and to identify local environmental and community-level risk-factors which compound the effects of natural phenomena contributing to reef degradation.

4.0 Background

This section reviews coral ecosystem services, threats, and the study site of this project.

4.1 Coral Reefs as Coastal Ecosystems

Corals are animal invertebrates in the phylum Cnidaria and class Anthozoa. They are found in warm, shallow ocean water typical of tropical latitudes. Although individual corals, referred to as polyps, can live solitarily in suspension, they are most commonly associated with the limestone reefs they construct in association with an algal symbiont called zooxanthellae. A mutualism between coral and zooxanthellae is formed by the give-and-take relationship during which coral polyps provide structure and nutrients obtained by suspension feeding to zooxanthellae and in turn, the photosynthetic zooxanthellae harness solar energy into carbohydrates which are shared with the polyps (West and Salm, 2003; National Geographic, 2019).

When a free-floating polyp attaches to a rock in association with zooxanthellae, it secretes a calcium carbonate base and begins to divide through binary fission into a colony of genetically identical clones. Polyps in a colony collectively function as a single organism. Coral reefs are formed when aggregates of coral colonies grow together and join to create a structurally complex matrix (National Geographic, 2019). The resulting environmental heterogeneity creates micro-niches which enable co-occurring fish and invertebrate species with similar life histories and ecological roles to undergo niche differentiation and resource partitioning. Through this partitioning, the pressure of competitive exclusion is partially released, allowing for greater coexistence between marine species which reside in reef environments. As a result, coral reef ecosystems possess disproportionately higher levels of localized biodiversity and species abundance than would be expected based on area alone (Obura and Grimsditch, 2009; National Geographic, 2019). This is especially important considering that coral reefs are generally found in oligotrophic, nutrient poor water (National Geographic, 2019). Without the symbiotic relationship between corals and zooxanthellae which allow them to harness solar energy, the lack of primary producers in coastal tropical waters would render the region nutrient poor, with very low biomass production, species abundance, and species diversity.

Despite covering less than one percent of Earth's surface (Obura and Grimsditch, 2009), coral reefs directly support one quarter of all ocean species (Knowlton, 2018). As structurally complex, marine biodiversity hotspots, reef ecosystems provide vital habitat, breeding grounds, nurseries, and vital ecosystem services to reef and pelagic organisms as part of the broader oceanic ecosystem.

4.2 Human-environment Interface

Coral reefs support more than 500 million people worldwide through fishing, employment, tourism, and coastal protection (Obura and Grimsditch, 2009). Collectively, these ecosystem services and extracted resources are estimated to value up to $375 billion dollars a year (Obura and Grimsditch, 2009). As primary producers of marine coastal regions, coral reefs directly support subsequent trophic levels which include invertebrates, fish, and marine mammals. As coral reef health declines, many populations of higher trophic levels are expected to decline as well. This is projected to hurt local economies in regions which depend on coral reef fisheries for subsistence and marine-based tourism, as well as pelagic fisheries worldwide through bottom-up trophic cascades. In addition to disrupting livelihoods and reducing food security for coastal communities, this impact could lead to a decline in the export of fish to international consumers, thus creating a gap in food security worldwide.

4.3 Coral Reef Threats and Response

When faced with environmental stress, corals expel their associated zooxanthellae in a process known as coral bleaching. Bleaching events can be caused by increases in ocean temperature, overexposure to sunlight, and air exposure during especially low tides, or exposure to harmful anthropogenic pollutants from urban and agricultural run-off (NOAA, 2018; West and Salm, 2003). Following a bleaching event, corals have an approximately 2 to 4 week period of time to recover (personal communication, Dr. Richard Walz). Repeated bleaching events, or an especially severe event due to prolonged stress, may result in complete coral mortality with no chance of recovery. Corals undergoing bleaching can be identified by the loss of colored pigment, creating a patchy white, or "faded" appearance. When total bleaching occurs, corals will turn completely white in color.

Other stressors which may compound the factors which contribute to bleaching and reef degradation include: increased nutrient load, which allows competitive algal growth on corals, sedimentation which inhibits photosynthetic activity, and the inhibition of coral calcium carbonate skeleton formation due to ocean acidification (West and Salm, 2003). Invasive species and corallivores which feed on coral polyps further threaten the health of, and cause stress to, coral reefs. Anthropogenic destruction and degradation due to irresponsible waste disposal, tourism, fishing, anchor damage, and resource extraction further threaten reef ecosystems (Linden et al., 2002; Obura and Grimsditch, 2009). Under increased stress, corals are more susceptible to pathogen infections. Therefore, pathogen infections can further be used as a proxy for coral reef health in addition to bleaching and algal growth (Obura and Grimsditch, 2009; Turley, 2016).

4.4 Coral Morphology, Associated Life History Strategies, and Implications for Coral Resiliency

Each coral colony takes on a different distinct growth form (Figure 1). These include branching types (arborescent, caespitose), columnar types (corymbose, digitate, columnar), tabular types, boulder types (honeycomb, golf ball, brain), encrusting types, foliose types, and free-living types (mushroom, slipper).

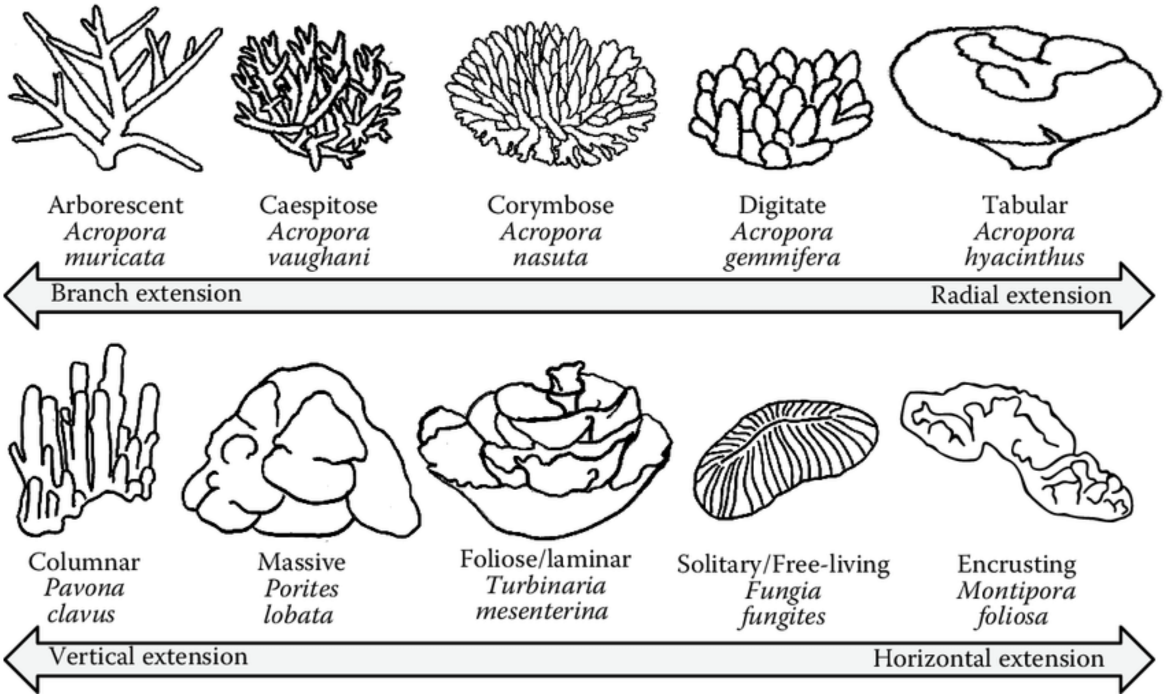

Figure 1. Image from Pratchett et al. (2015) displaying the ten most common growth forms on a scale of branching extension to radial extension, and vertical extension to horizontal extension.

Each growth form has an associated life history strategy with which it most commonly aligns (Darling et al., 2012). Coral life histories influence coral reef dynamics, response to stress, and resiliency (Darling et al., 2012; Grimsditch et al., 2017). Therefore, incorporating this knowledge into our framework of assessing reef health will give us a better understanding of reef dynamics and temporal trends in resistance (Grimsditch et al. 2017).

Coral growth forms with higher surface-area to volume ratios experience higher exposure to environmental stressors such as excess sun exposure, toxins, and temperature, thereby increasing their susceptibility to bleaching and degradation due to disturbance. Branching (i.e. arborescent, caespitose, corymbose), digitate, columnar, and tabular coral growth forms have among the highest surface area to volume ratios. These coral growth forms can be categorized as ‘competitive’ species which dominate in non-disturbed environments due to their fast growth pattern and ability to out-compete adjacent corals for space and resources (Darling et al., 2012). However, since growth forms in this group are typically branching (i.e. *Acropora*), they face the trade-off of having a growth form which makes them particularly susceptible to damage and disturbance based on their physiology and morphology (Grimsditch et al., 2017). In addition to increased exposure to environmental stressors, a high surface area to volume ratio makes them more structurally feeble compared to encrusting corals, therefore, exposing them to greater risk against anchor damage and irresponsible snorkeling activities.

In contrast, massives (i.e. honeycomb, golf ball, brain), foliose/laminar, solitary/free-living (i.e. mushroom, slipper), and encrusting growth forms, which are generally all low-lying with a low surface area to volume ratio, can be classified as ‘stress tolerant’ (Darling et al., 2012). This classification is based on their ability to conserve energy and resist degradation due to increased exposure to environmental stresses, characteristically high fecundity, and broadcast spawning reproduction which allows them to reproduce when individuals are located far away from one another in low densities. However, their slow growth makes them an inferior competitor prone to being shaded out by more dominant species (Grimsditch et al., 2017).

Corals with ‘weedy’ life-histories are small, have fast growth rates, are short-lived, and have high turnover in their populations, which allows them to hold widespread distributions. These individuals can take a variety of growth forms. However, they remain competitively inferior to other corals and remain at-risk of being shaded-out, so they rarely form large colonies (Darling et al., 2012). ‘Generalist corals’ have a mix of the above traits, which enables them to survive in a range of habitats and under various exposures to environmental degradation (Grimsditch et al., 2017). Most coral reefs are made up of an array of coral growth forms which utilize inherently different life-history strategies, take on different growth forms, and are of different sizes.

4.5 Study Area

Misali is a 0.9km^2 island located at 5°15’S 39°36’ E (Kertesz, 2000:7), 10km off the west coast of Pemba Island in the Zanzibar Archipelago, Tanzania (Levine, 2015). Misali is an oceanic island, with a steep drop off to the adjacent Pemba Channel which has a maximum depth of 800m. This drop-off creates an upwelling of cold, nutrient-rich water from the channel into nearby reefs, thereby increasing biomass production and serving as a buffer against heat-stressed coral bleaching.

Misali Island is surrounded by 9.4km of fringing coral reef (Kertesz, 2000:7). It is one of the most biodiverse areas in the archipelago, representing 40 species of hard coral out of the 60 found in Tanzania (Kertesz, 2000:7). This diversity is extremely important to the dispersal of coral larvae along the Pemban coastline because the strong tidal current around Misali serves as an effective agent of dispersal (Poonian, 2008).

Figure 2. Google Map images marking the location of Misali Island, off the east coast of Tanzania in East Africa (left) and a close-up of Misali Island showing shallow fringing reefs (light blue) and the drop-off to the Pemba Channel (dark blue) (right).

Human communities in the Zanzibar Archipelago are highly dependent on coral reef fisheries for subsistence and marine-based tourism for income. The communities surrounding Misali are no exception (Levine 2015). The high productivity of this region supports well developed fisheries and contributes to the area's designation as a biodiversity hotspot and its appeal as a tourist destination (Levine 2015).

In order to protect the area, initiatives were taken to conserve the reefs while engaging local communities and promoting sustainable fishing practices. In 1998, following a severe bleaching event that damaged more than 80% of corals in the Western Indian Ocean (WIO) (Obura, 2002), the Misali Island Marine Conservation Area (MIMCA) was established as a 22km^2 marine protected area (Figure 3; Levine, 2015). MIMCA was initiated as a collaboration between the government, fishermen from local communities, and sponsors, including CARE

International, Menai Bay Conservation Area (MBCA), World Wide Fund for Nature (WWF), Chumbe Island Coral Park (CHICOP), and Mnemba Island lodge and management (Levine, 2015). MIMCA restricted fishing in the larger MPA and created a 1.4km^2 strict non-extraction zone, where fishing was prohibited and regulations well-enforced by regular ranger patrols (Levine, 2015). However, illegal dynamite fishing and the use of illegal kigumi nets persisted (Levine, 2015:6). In 2006, funding from the World Bank and Global Environment Facility led to the development of the Pemba Channel Marine Conservation Area (PECCA), a ~1000 km^2 area which encompassed and subsequently phased out MIMCA (Figure 3; Levine, 2015).

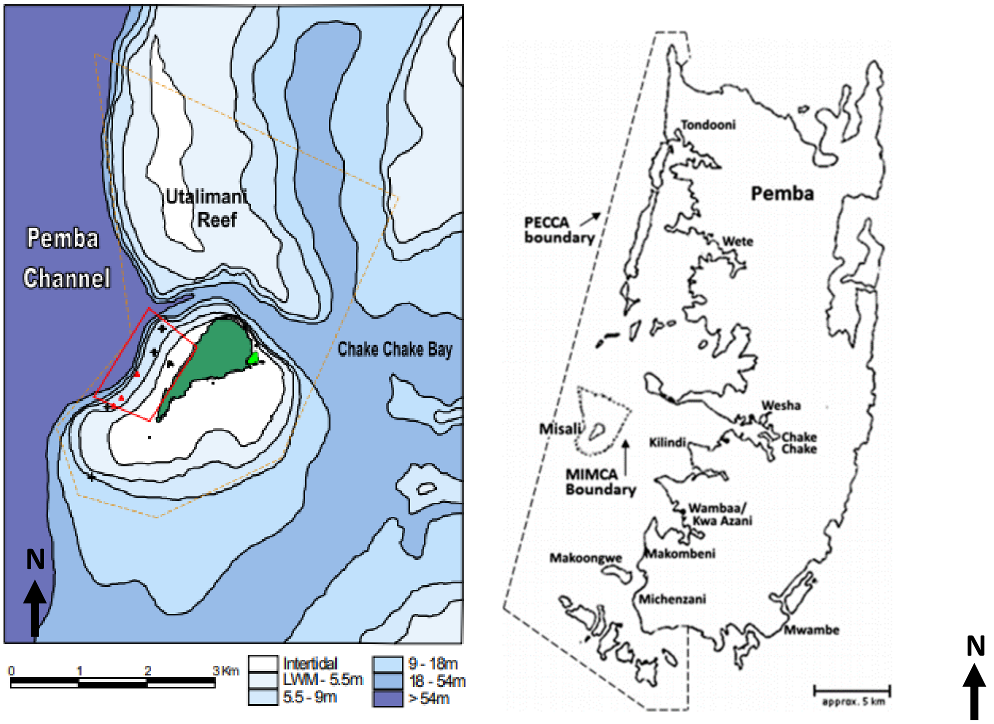

Figure 3. The image to the left shows the MIMCA non-extractive zone (solid line) and protected zone (dotted line) surrounding Misali Island (image from Richmond and Mohammed, 2001:9). The image to the right shows the new PECCA boundary in comparison to the previous MIMCA boundary surrounding Misali Island (image from Levine, 2015:4).

Today, the initial, core non-extraction zone put in place by MIMCA maintains its protection status under PECCA and continues to be managed by local rangers (personal communication, rangers of Misali). While rangers continue to patrol the larger protected area to enforce fishing regulations, the increased size of the marine protected area makes it difficult to discipline poachers and enforce broader regulations.

In the Western Indian Ocean, coral bleaching is increasingly leading to reef mortality, degradation, and the loss of habitat for marine and coastal species (Linden et al., 2002; Obura, 2002). In the Zanzibar Archipelago, these adverse effects on reefs are only projected to become more apparent as human population growth and increased industrialization continue to cause direct and indirect stress on the ecosystem. In reefs surrounding Misali, this process may be exacerbated by the anthropogenic stress of resource extraction and over-fishing. Previous studies on the Zanzibar Archipelago have reported evidence of reef fishery overexploitation (Linden et al., 2002; Obura, 2002), however coral health and the effects of fishing and resource extraction are specifically understudied on Misali fringing reefs (Jones, 2017).

In this study, coral health will be assessed at two contrasting fringing reefs off Misali Island. The first zone, referred to as the Extraction Zone (EZ), is a fringing reef located on the north-west side of the island. This area has been under the protection of MIMCA since 1998 and then was transferred to the protection of PECCA in 2006 (Levine, 2015). Resource extraction is allowed in this zone and fishing by Zanzibaris is a common occurrence in this location. The second zone, referred to as the Non-Extraction Zone (NEZ), is located on the far west side of the island. This area has been a part of the core non-extraction zone under the protection of MIMCA since 1998, and has since continued to maintain its status as a non-extraction zone under PECCA (Levine, 2015).

At the extraction zone site, corals grow in patches on rocky outcrops along the edge of a steep reef slope to depths of 20m (Kertesz, 2000:7). At the non-extraction zone site, corals grow along a large reef flat and along the adjacent steep slope to depths of 70m (Kertesz, 2000:8). The EZ site has been reported to have a similar topographic and reef structure to the NEZ site (Jones, 2017:13), and was therefore chosen as a study location to minimize the effects of environmental variation on coral size, morphology, and community structure (Figure 3).

Figure 4. Google Map image with overlaid GPS coordinates marking the location of the extraction and non-extraction zone transects at Misali Island (white solid lines).

4.6 Susceptibility of Misali Reefs

At the start of this study, a bleaching alert was made for northern Tanzania's reefs and the broader Western Indian Ocean (CORDIO, 2019) as a result of high than average water temperatures in the region. In addition, an extreme low spring tide was projected to occur on April 21st, 2019. Low spring tides expose shallow reefs to increased air, sunlight, and heat, thereby further increasing the likelihood of bleaching. Coupled together, significant bleaching was predicted to occur at Misali reefs during the independent study project.

Misali was chosen as a study site since its reefs are expected to be in better health than others in the archipelago, thanks to their isolation from urban and agricultural run-off, their protection status under PECCA, and the cool upwelling of water from the adjacent Pemba Channel. If reef health is poor at Misali, it can be expected to be worse at other fringing reefs along coastal Tanzania. Other reefs in the archipelago and along coastal Tanzania experience greater anthropogenic influence from pollution and physical damage, but experience similar bleaching alerts and tides. Therefore, Misali's coral reefs can be used as a relative indicator to gauge the health and status of reefs across the Zanzibar Archipelago and the broader region of coastal Tanzania.

5.0 Methodology

To assess coral reef health and human impacts on reef systems, rapid assessments are often used, during which researchers lay transects and report coral bleaching and other signs of stress, including disease and algal cover (Rogers et al., 2014; Turley, 2016). This study employs similar methods to assess coral health and biodiversity.

5.1 Survey Methods

Surveys were conducted in two zones around Misali Island for a duration of 28 days in April, 2019. Parallel 25m linear transects (n =31 total) were laid at least 20m apart in the extraction zone (EZ) and non-extraction zone (NEZ). GPS coordinates of transect locations were recorded using a Garmin Etrex 20x, with the position format set to UTM, map datum set to New Arc 1960. Water depth at the start and end of each transect was estimated visually, averaged, and rounded to the nearest half meter based on estimates of the principal investigator (R_1) and SIT student, Natalie Givens (R_2). The rugosity of each transect was estimated visually based on an ordered, categorical scale created by R_1 and R_2. The categories (1-5) were designated so that a rugosity of 1 was very flat with very few to no corals, a rugosity of 2 had a few smaller corals (bomies), a rugosity of 3 had more or larger corals than 2, a rugosity of 4 had more or larger corals than 3 (large bomies or a full reef), and 5 was a well-established, structurally complex reef or series of massive bomies. For each transect, R_1 and R_2 swam the length of the tape and assigned a rugosity level based on the above criteria. Rugosity was averaged and rounded to the nearest 1.

All Scleractinian (stony) corals located within 1m of the transect were recorded. Growth form was documented (13 categories: arborescent, caespitose, corymbose, digitate, tabular, columnar, honeycomb, golf ball, brain, encrusting, foliose, mushroom, slipper), and each coral colony was inspected for evidence of bleaching. Bleaching percent cover was estimated for each colony visually and categorized as 0-5%, 6-25%, 26-50%, 51-75%, 76-95%, or 96-100%.

Additional ad hoc observations of damage to coral individuals (corallivore evidence, anchor damage, pathogen presence, algal cover), transects (drastic temperature differences, water visibility, wave action), and sites (corallivore evidence, anchor damage, pathogen presence, algal cover, presence of fishermen, detritus, topographical differences) were recorded. The presence of *Drupella* snails, which create abrasions while feeding and increase coral susceptibility to pathogen infections (Turley, 2016), and the presence of crown-of-thorns starfish, a corallivore which consumes coral polyps (Turley, 2016), were specifically searched for and recorded as additional proxies of reef health.

Photographs were taken of corals in the extraction zone and non-extraction zone before and after the extreme low spring tide event on April 21st using a GoPro Hero underwater camera.

Photographs were taken to track bleaching and potential re-recruitment of zooxanthellae by corals after being subjected to the increased stress of air, heat, and sun over-exposure during this event.

5.2 Data Management and Analysis

Data were entered in Excel following each data collection event. During data entry, each coral colony was assigned an individual identification number. The date of data collection was recorded as the number of days after January 1st, 2019 (where January 1st = day 1). Transect number was assigned and recorded. The site was recorded using 0,1 coding, where 0 = NEZ and 1 = EZ. Inshore and outshore water depths were recorded for each transect and averaged in excel to get one water depth measurement for each transect. Inshore and outshore coordinates were recorded for each transect. Rugosity was entered, along with growth form and ad hoc observations about coral individuals, transects, and sites. A category was later created using 0,1 coding where 0=the dates prior to the April 21st extreme spring low tide, and 1 = the dates following the spring low tide.

Data exploration and analyses were performed using R Studio 1.1.463. Coral bleaching percentages were converted from the ordered factors of 0-5%, 6-25%, 26-50%, 51-75%, 76-95%, and 96-100%, to the middle number of each category (2.5, 15.5, 38.0, 63.0, 85.5, and 98.0). By doing so, the data type was able to be converted to numeric for use in further analyses. Inshore and outshore water depths were averaged for each transect.

Coral bleaching severity and coral growth form occurrences were identified in the extraction zone and non-extraction zone and pooled for a collective analysis at both sites. Percentages were found using the \`dplyr\` R package and plots were created using the \`ggplot\`

function through the `tidyverse` R package. Multiple regression linear models were performed using the `lm` function from the `stats` R package to test whether coral bleaching severity correlates with the individual effects of site, growth form, and time before or after the spring low tide event (Appendix).

Linear model (LM) 1 (Appendix, Model 1) was performed to determine the individual effects of site, rugosity, growth form, and exposure on coral from the spring low tide bleaching when all other independent variables are held constant. LM 2 (Appendix, Model 2) was performed to isolate the most significant terms to improve the precision on the estimated correlation between growth form and the occurrence of the low spring tide on coral bleaching. Water depth was omitted from these analyses due to the presence of 417 NAs which would skew the outcome of the model. By removing water depth, the multiple regression linear model is better able to predict the effects of the remaining significant factors. One observation was also removed from the performed regression models because it was shown to impact the models more than any single observation statistically should. Out of 1329 observations, the removed individual (observation number 600) was the only tabular colony represented.

6.0 Results

Thirty-one transects were laid-out and studied during the 28-day period. Fourteen transects were in the non-extraction zone, and seventeen were in the extraction zone.

6.1 Coral Growth Forms

A total of 1,329 observations on coral colonies across the two zones were studied. This sample was made up of coral colonies of ten growth forms, of which, 26% were encrusting (n=346), 20.9% were caespitose (n=278), 18.1% were arborescent (n=241), 17.1% were corymbose (n=227), 9.7% were digitate (n=129), 5.2% were golf ball (n=69), 1.4% were honeycomb (n=18), 0.8% were brain (n=11), 0.7% were mushroom (n=9), and 0.1% were tabular (n=1)(Table 1).

Table 1. Percent composition of coral growth forms found in the non-extraction zone (NEZ), extraction zone (EZ), and total area surveyed. Starred entries indicate substantial differences in the growth form composition of corals between the two zones. The EZ has substantially more caespitose corals than the NEZ. The NEZ has substantially more encrusting corals than the EZ.

Growth Form	**Total (%)**	**NEZ (%)**	**EZ (%)**
Arborescent	18.1	11.2	21.0
Caespitose	20.9	**1.6***	**28.8***
Corymbose	17.1	17.9	16.7
Digitate	9.7	8.1	10.4
Tabular	0.1	0.0	0.1
Honeycomb	1.4	1.6	1.3
Brain	0.8	0.8	0.8
Golf ball	5.2	6.2	4.8
Mushroom	0.7	0.8	0.6
Encrusting	26.0	**51.9***	**15.5***

In the non-extraction zone, encrusting was the most commonly observed coral growth form at 51.9% (n=200), followed by corymbose at 17.9% (n=69), and arborescent at 11.2% (n=43). Meanwhile, in the extraction zone, caespitose was the most common growth form observed at 28.8% (n=272), followed by arborescent at 21.0% (n=198), and corymbose at 16.7% (n=158)(Table 1).

6.2 Coral Bleaching by Site

Observations from coral reef sites at Misali Island reported that 63.4% of corals (n=843) observed exhibited substantial signs (>5% of surface area) of bleaching. In summary, 50.9% of corals (n=676) were more than 25% bleached, and 36.1% of corals (n=480) were more than 75% bleached (Table 2; Figure 5). In the non-extraction zone, 39% of coral colonies (n=150) observed exhibited substantial signs (>5% of surface area) of bleaching, 24.1% of corals (n=93) were more than 25% bleached, and 15.3% of corals (n=59) were more than 75% bleached. Meanwhile in the extraction zone, 73.4% of coral colonies (n=693) observed exhibited substantial signs (>5% of surface area) of bleaching, while 61.8% of corals (n=583) were more than 25% bleached, and 44.6% of corals (n=421) were more than 75% bleached (Table 2; Figure 6). There was no statistically significant correlation between site and coral bleaching severity (t=1.58, std. error = 2.04, $p > 0.05$ (Appendix, Model 1).

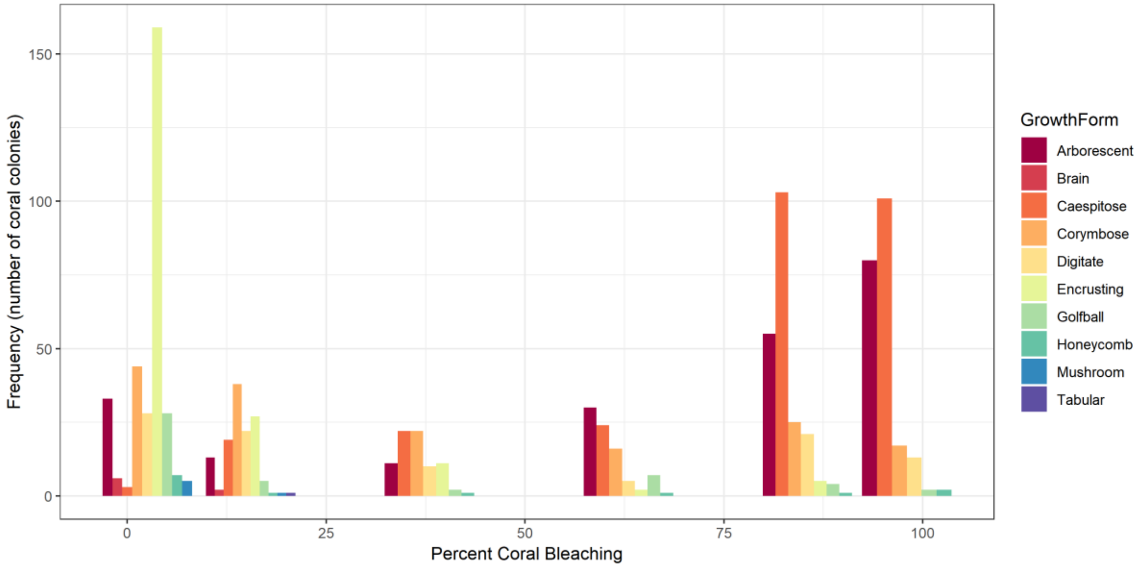

Figure 5. Frequency of coral colonies by growth form observed in each percent bleaching category at all sites surveyed at Misali Island.

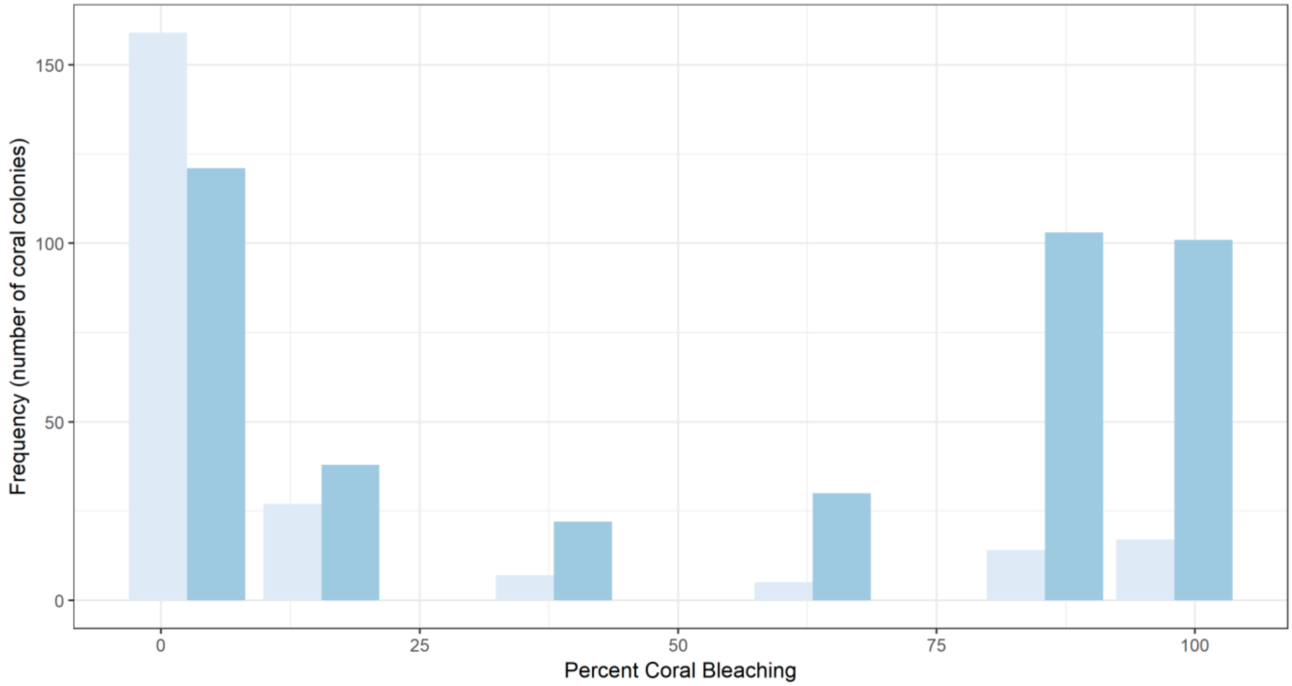

Figure 6. Frequency of coral colonies, reported by site, in each percent bleaching category surveyed. The non-extraction zone (light blue) has a higher frequency of corals in the 0-5% bleaching category than the extraction zone (dark blue). Meanwhile, the extraction zone has a higher frequency of corals in the 76-95% and 96-100% bleaching categories.

Table 2. Percent bleaching of corals found in the non-extraction zone (NEZ), extraction zone (EZ), and total area surveyed. Starred entries indicate substantial differences in the percent bleaching of corals between the two zones. The NEZ has substantially more corals in the 0-5% category than the EZ, meanwhile the EZ has substantially more corals in the 96-100% category than the NEZ.

Bleaching (%)	**Total (%)**	**NEZ (%)**	**EZ (%)**
0-5	36.6	**61.0***	**26.6***
6-25	12.6	14.8	11.7
26-50	7.4	5.2	8.3
51-75	7.4	3.6	8.9
76-95	18.2	7.8	22.5
96-100	17.9	**7.5***	**22.1***

6.3 Coral Bleaching by Growth Form

Arborescent corals and caespitose corals were found to have the highest percent bleaching (median = 85.5%, SE arborescent = 2.38, SE caespitose = 1.56), followed by corymbose and digitate corals (median = 38.0%, SE corymbose = 2.43, SE digitate = 3.37), tabular corals (median = 15.5%, SE = NA), then by brain, encrusting, golf ball, honeycomb and mushroom corals (median = 2.5%, SE brain = 1.59, SE encrusting = 0.88, SE golf ball = 3.88, SE honeycomb = 9.20, SE mushroom = 1.44; Figure 6). All growth forms significantly correlate with bleaching severity ($p < 0.001$; Appendix, Models 1 and 2).

The predicted mean percent bleaching of caespitose growth forms was found to be 12.16 greater than the mean percent bleaching of arborescent growth forms ($t = 4.68$, std. error = 2.60, $p = 3.21e-06$; LM 2). The predicted mean percent bleaching of corymbose growth forms was found to be 26.51 less than the mean percent bleaching of arborescent growth forms ($t = -9.57$, std. error = 2.77, $p < 2e-16$; LM 2). The predicted mean percent bleaching of digitate growth forms was found to be 23.10 less than the mean percent bleaching of arborescent growth forms ($t = -7.16$, std. error = 3.23, $p = 1.37e-12$; LM 2). The predicted mean percent bleaching of honeycomb growth forms was found to be 34.45 less than the mean percent bleaching of arborescent growth forms ($t = -4.78$, std. error = 7.20, $p = 1.91e-06$; LM 2). The predicted mean percent bleaching of brain growth forms was found to be 60.58 less than the mean percent bleaching of arborescent growth forms ($t = -6.67$, std. error = 9.09, $p = 3.83e-11$; LM 2). The predicted mean percent bleaching of golf ball growth forms was found to be 47.00 less than the mean percent bleaching of arborescent growth forms ($t = -11.48$, std. error = 4.09, $p < 2e-16$; LM 2). The predicted mean percent bleaching of mushroom growth forms was found to be 62.28 less than the mean percent bleaching of arborescent growth forms ($t = -6.23$, std. error = 10.01, $p = 6.48e-10$; LM 2), and the predicted mean percent bleaching of encrusting growth forms was found to be 58.03 less than the mean percent bleaching of arborescent growth forms ($t = -23.36$, std. error = 2.49, $p < 2e-16$; LM 2).

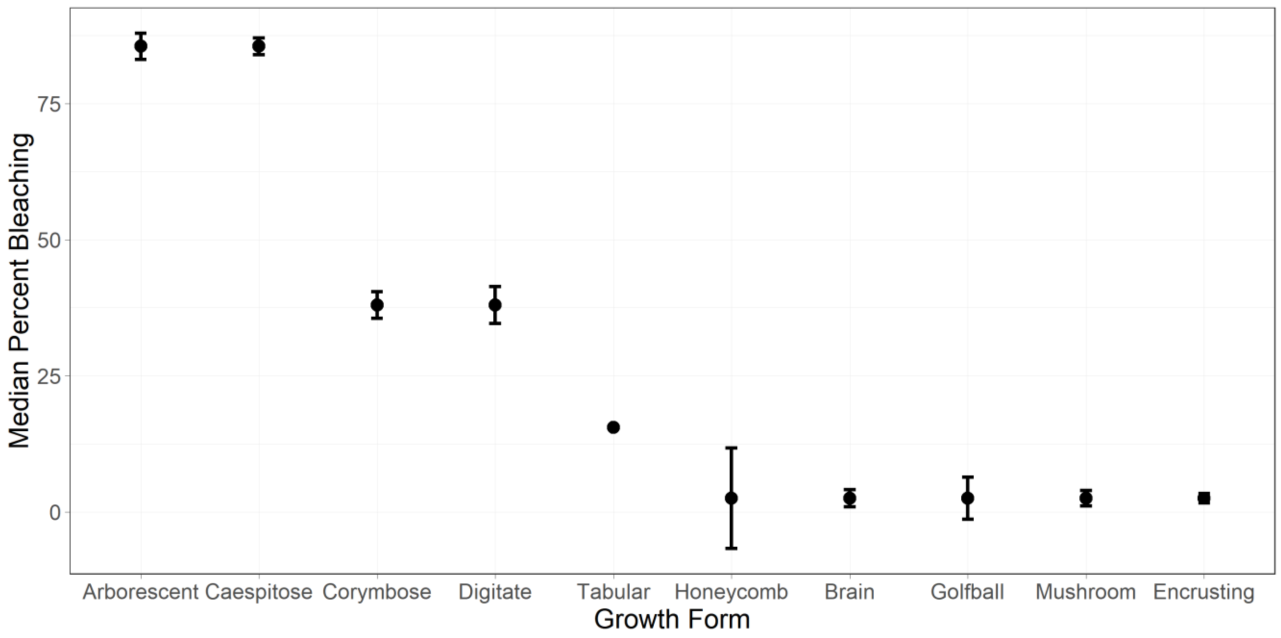

Figure 6. Median percent bleaching of coral growth forms observed in the extraction and non -extraction zones at Misali Island. Arborescent and caespitose have the highest median percent bleaching (85.5%), followed by corymbose and digitate (38.0%), tabular (15.5%), and honeycomb, brain, golf ball, mushroom and encrusting (2.5%) growth forms.

6.4 Coral Bleaching Over Time

Average percent bleaching increased over the 28-day study period for caespitose, corymbose, digitate, encrusting, golf ball, honeycomb, and mushroom growth forms (Figure 7). Average percent bleaching decreased over the 28-day study period for arborescent corals (Figure 7). There is insufficient data to track average bleaching over time for tabular growth forms (n=1). The predicted mean percent bleaching of corals after the April 21st spring low tide is 13.01 greater than before the spring low tide (t = 7.53, std. error = 1.73, p = 9.16e-14; LM 2).

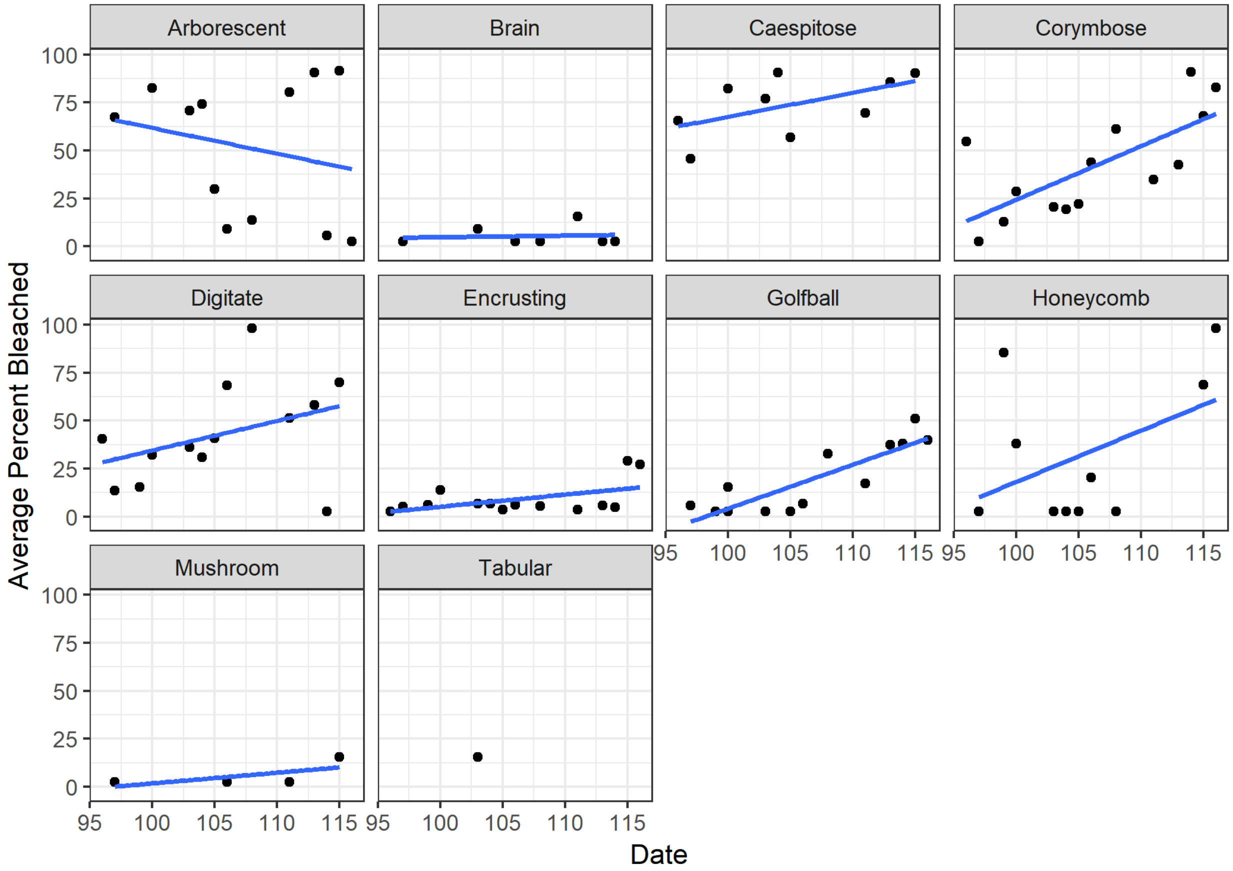

Figure 7. Average percent bleaching of coral growth forms observed in the extraction and non -extraction zones at Misali Island over a 28-day period in April 2019. Date is reported as the number of days past January 1st, 2019. Bleaching was found to increase over time for all growth forms observed except arborescent corals.

6.5 Qualitative Observations

Coral growth form abundance differed drastically between the extraction and non-extraction zones (Figure 1). The extraction zone was heavily dominated by caespitose, arborescent, and corymbose corals - all of which are growth forms which are highly branched, with a high surface area to volume ratio which increases their exposure to environmental stressors and increases their likelihood to undergo bleaching. Meanwhile, the non-extraction zone was dominated heavily by encrusting growth forms which have the lowest surface area to volume ratio possible and are most commonly associated with a stress-tolerant life history strategy.

The presence of corallivore species, including Crown of Thorns Starfish (*Acanthaster planci*) and *Drupella* snails were noted in both the NEZ and EZ.

Over the 28-day study period, seven days were spent in the non-extraction zone, during which time more than 100 fishermen were counted illegally fishing on the reef flat, slope, and intertidal zone. While more than 25 vessels were counted in the non-extraction zone during this time, most of the fishermen were observed fishing and collecting organisms in the intertidal and subtidal zones on foot.

7.0 Discussion

This study investigated coral reef health and bleaching in fringing reefs in the extraction and non-extraction zones around Misali Island. This section discusses the complexities of the results obtained in this study.

7.1 Coral Bleaching

Bleaching was found to be extensive for all growth forms in both the extraction and non-extraction zones (Table 2). The prediction that bleaching intensity correlates with surface area associated with growth forms was supported by this study; branching arborescent and caespitose corals were the most heavily bleached, followed by intermediate corymbose and digitate growth forms, then by those forms with the lowest surface area to volume ratio (Figure 7; Table 2).

Bleaching frequency did not differ significantly between the extraction and non-extraction zones (Figure 6; Table 2). However, the extraction zone was found to have more overall bleaching than the non-extraction zone (Table 2). Initially, contrasting study sites in the extraction and non-extraction zones were selected with the aim of teasing apart whether anthropogenic resource extraction correlates with bleaching and the overall health of coral reefs. However, no conclusions can be drawn from differences in protection, over-fishing, or resource extraction considering the observed presence of fishing activities in both study areas. Not only is fishing illegal in the NEZ, but the constant foot traffic through this sensitive zone by fishermen damages delicate seagrass beds, dislodges soft corals, and breaks Scleratinian corals (personal observation). In contrast, most of the fishing activities in the EZ used basket traps and gill nets suspended from fishing vessels. In the two instances that basket traps in this zone were seen at a close range, considerable damage to soft corals and Scleartinian corals was observed. Similarly, substantial anchor damage to Scleratinian corals was observed on more than seven occasions in the EZ study site.

Due to the extensive fishing practice in both the EZ and NEZ, observed differences in bleaching levels and reef health between the two zones are more likely attributed to differences in environmental factors and the morphologies and life-history strategies of the corals present in each of the two zones.

The non-extraction zone is located directly adjacent to the Pemba Channel on the west side of Misali Island, with a steep drop-off from the reef flat to a depth of 800m. This creates an upwelling of cool, nutrient-rich water from the channel which increases reef productivity and offers a buffer against heat-stress and bleaching in the adjacent reefs of the non-extraction zone. Meanwhile, the study site in the extraction zone is located on the northeast side of Misali Island, adjacent to a shallow channel between Misali Island and Pemba Island. The upwelling of water directly from the Pemba Channel to the non-extraction zone may contribute to lower levels of bleaching observed there (Table 2). However, given the EZ and NEZ study sites are only within a few kilometers of one another, these differences are more likely attributed to inherent differences in coral growth form abundances between the two sites. Since the extraction zone has substantially more branching corals than the non-extraction zone, it is expected that more overall bleaching would be observed there (Table 1). Similarly, it is expected that the non-extraction zone, which is heavily dominated by encrusting growth forms, would be stress-tolerant and more resistant to bleaching.

The low coral growth form diversity observed in the non-extraction zone compared to the extraction zone is likely a partial relic of the 1998 severe bleaching event which led to widespread bleaching and coral mortality in the NEZ initially protected under MIMCA (Levine, 2015). When the bleaching event occurred in 1998, branching growth forms and those with greater surface area to volume ratios in the zone likely were killed off, leaving more resistant boulder and encrusting forms behind to continue to grow and re-establish in the area (Jones, 2017).

As predicted by the CORDIO bleaching alert for the Western Indian Ocean (CORDIO, 2019), coral bleaching was found to increase in severity over the study period across most coral growth forms (Figure 7). This phenomenon most likely can be attributed to higher mean water temperatures in the region (Gates et al. 1992; Brown, 1997) and the effects of over-exposure of the corals to heat, sunlight, and air during the April 21st spring low tide event (NOAA, 2018; West and Salm, 2003). Bleaching severity was confirmed to significantly increase following the spring low tide event (Appendix, Model 1 and 2). However, it is important to note that bleaching was already observed to be extensive before the spring low tide event. Therefore, bleaching events on Misali reefs were more widespread than this isolated event.

The average bleaching severity of corymbose, digitate, and honeycomb growth forms was found to increase substantially over the study period (Figure 7). The average bleaching severity for caespitose growth forms increased but at a slower rate than for corymbose, digitate and honeycomb growth forms. This is likely because caespitose corals were already highly bleached at the beginning of this study, so eventually bleaching intensity could no longer increase and began to plateau. The average bleaching intensity of golf ball corals increased slowly over the study period (Figure 7). This is evidence of the resistance these growth forms have against bleaching, likely due to their low surface area to volume ratio. Mushroom and brain corals experienced very low average bleaching severities which remained low throughout the study period, for the same reason.

The only growth form which did not experience an increase in bleaching severity throughout the study period was arborescent growth forms (Figure 7). However, this can be attributed to the susceptibility and resilience of species which take on this growth form (Darling et al., 2012). There was one species of arborescent coral (Image 1) which was consistently observed in all transects to experience less bleaching than other species of arborescent corals. Throughout the study period, the number of coral colonies of this species increased across the transects surveyed, particularly in the non-extraction zone. Meanwhile, all other species of arborescent corals observed in this study consistently continued to experience more frequent and severe bleaching events. Therefore, the decline in bleaching severity reported in Figure 7 should not be considered as evidence of bleaching recovery or re-recruitment of zooxanthellae. In fact, it is important to note that even this seemingly stress-resistant arborescent species was observed to experience an increase in bleaching frequency and severity during the last week of the study.

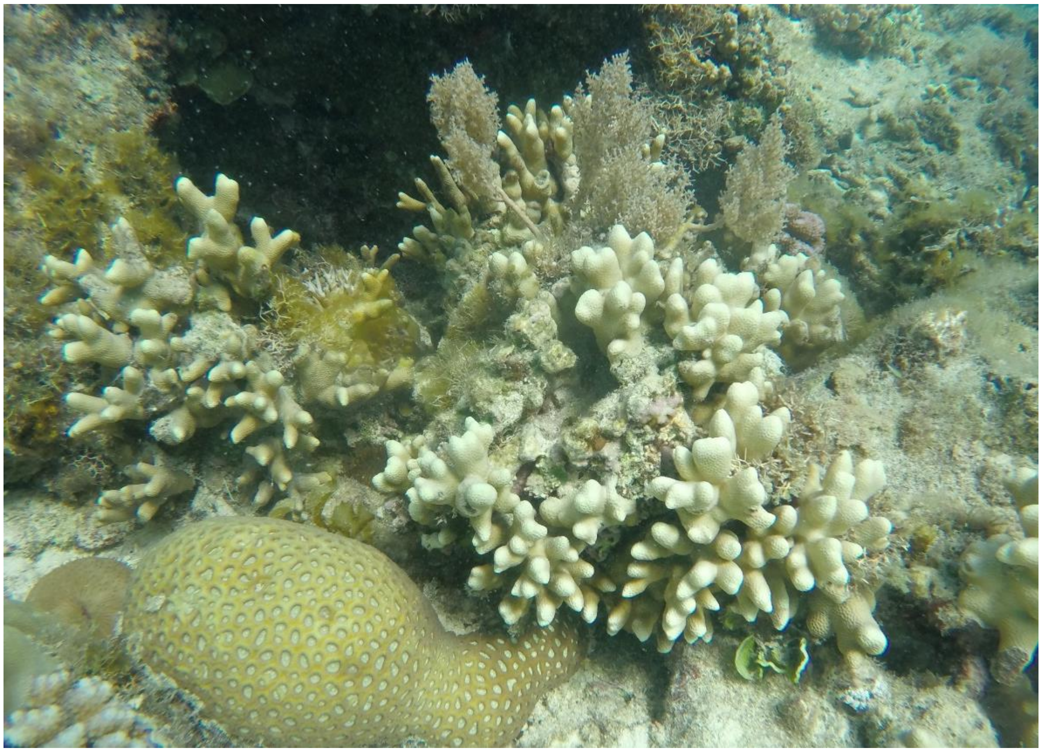

Image 1. Stress-resistant species of arborescent coral found at Misali Island, Tanzania. This photo was taken by the principal investigator on April 24th, 2019 in the non-extraction zone located to the west of the island.

The stress-resistant growth forms identified in this study may be good candidates to cultivate and grow for reef restoration plans as heat stress increases in future years due to climate change and anthropogenic influences. However, it is not ideal that the most stress-resistant corals appear to be those which are the slowest growing based on life-history strategy. This may prove to be problematic in the future. During the time it will take to grow these individuals to a size desirable for restoration practices, branching and intermediate growth forms are likely to experience extensive mortality. As a result, once biodiverse reefs will transition to urchin barrens and will cause mass mortality events for fish and invertebrates which rely on the reefs for food, breeding grounds, nurseries, and habitats.

Recovery from this bleaching event cannot yet be predicted. Through the study period, no re-recruitment of zooxanthellae was observed at the study sites. Since more than two weeks passed in a total bleached phase, it is unlikely that these corals will recover (personal communication, Dr. Richard Walz).

Following the current trends, it is likely that in the next few years the branching corals will be the first to experience extensive to total mortality around Misali Island. This will likely concurrently align with a continued increase in bleaching and the mortality of intermediate and low surface area to volume growth forms. In the next few years, it is likely that encrusting corals, which tend to be stress-resistant, will become the most dominant growth form across Misali's reefs. Not only will this homogenization decrease the available niches on the reef, increasing competition and decreasing productivity, but it will also lead to the inevitable exclusion and mortality of many fish and invertebrate species which depend on reef habitats. There may be catastrophic changes in the food web: the collapse of trophic cascades and extensive damage to reef-based fisheries.

7.2 Potential Sources of Error

Potential sources of error in this study include mis-estimating the percentage of bleaching of coral colonies. This was especially likely on days with poor water clarity and deeper water depths which caused some corals to appear more bleached than they may have been. However, the results of this study match the already known trend between coral growth form surface area and percentage of bleaching, suggesting that the bleaching estimates made had a notable degree of precision and accuracy.

Data analyses could have been improved by considering data collected along the same transect as dependent rather than as independent events. Such an approach would have minimized pseudoreplication in the data created by local environmental factors which impact coral community composition and bleaching intensity.

Furthermore, GPS coordinates collected at the start and end of each 25m transect appear to have a degree of error and are off by a distance of >20m. This was likely a result of equipment malfunctioning or inadequate time to allow for satellite synchronization.

8.0 Conclusion

This study aimed to assess coral reef health and bleaching in fringing coral reefs around Misali Island, Tanzania. No overall significant differences in bleaching frequency or intensity were observed between the resource extraction and non-extraction zones. Bleaching was observed to be extensive across all coral growth forms and was found to collectively increase over the study period in frequency and intensity. Bleaching is only projected to intensify in the coming years as ocean temperatures continue to rise. To mitigate stress on coral reefs and improve reef resiliency, care should be taken to minimize anthropogenic damage and over-fishing as compounding factors that damage reef health.

9.0 Recommendations

Study methods may be improved by expanding the number of study sites to all the reefs surrounding Misali Island. Collecting data from a greater number of transects and longer transects than 25m would have been preferred to increase sample size and minimize standard error. Future researchers are encouraged to build upon this study by collecting data about environmental factors such as water depth, distance offshore, and water temperature in order to analyze the impact these variables have on bleaching. It would be preferred if coral colonies could be identified to the genus or species level in order to better identify individuals which are stress-resistant, and which species would make good candidates for use in any reef restoration projects going forward.

Bleaching is projected to intensify in the coming years as ocean temperatures continue to rise. To mitigate stress on coral reefs and improve reef resiliency, care should be taken to minimize anthropogenic damage to marine environments and the over-exploitation of resources. This goal may be accomplished by increasing ranger patrols around Misali Island to prevent poaching and illegal fishing in the non-extraction zone. Buoys should be placed around the ranger station and visitor center on Misali Island so boats anchor without damaging fragile soft corals and Scleratinian corals on the fringing reef. In addition, the use of basket traps should be prohibited, as these traps have been observed to repeatedly dislodge and crush soft corals, and to break the branches of Scleratinian corals.

A previous study found that a loss of 10 percent of live corals led to a decline in fish abundance and that a loss of 60 percent of live corals led to a substantial decline in fish biodiversity (Pratchett et al., 2011). To prevent a significant loss of the live corals which resident fish and invertebrate populations depend on for food, nurseries, and breeding areas, active reef restoration practices should be put into place at Misali Island. One such method of restoration is farming stress-resistant coral species within the protected, non-extraction zone near Misali Island. By increasing the percentage of live coral cover using stress-resistant coral species, this restoration initiative may slow declines in fish abundance and decrease the effects reef degradation will have on local fisheries. Furthermore, by introducing and supporting the growth of stress-resistant corals, polyps of these resistant growth forms will flourish and disperse to other Pemban reefs via the strong currents around Misali Island. In this way, growing stress-resistant corals around Misali has the advantage of indirectly improving the resilience of other Pemban reefs going forward.

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11.0 Appendix

<u>Model 1</u>

Final form of the multiple regression linear model that was used for site data predictions.

$$\begin{aligned}\mu = \beta_0 + \beta_1 I(site = 1) + \beta_2 I(rug = 2) + \beta_3 I(rug = 3) + \beta_4 I(rug = 4) \\ + \beta_5 I(gf = brain) + \beta_6 I(gf = caespitose) + \beta_7 I(gf = corymbose) \\ + \beta_8 I(gf = digitate) + \beta_9 I(gf = encrusting) + \beta_{10} I(gf = golf\ ball) \\ + \beta_{11} I(gf = honeycomb) + \beta_{12} I(gf = mushroom) \\ + \beta_{13} I(springphase = 1)\end{aligned}$$

Where:

μ = predicted bleaching severity

site = non-extraction zone (location 0) or extraction zone (location 1)

rug = rugosity

gf = growth form

spring phase = before the April 21st, 2019 low spring tide (spring phase = 0) or after the April 21st, 2019 low spring tide (spring phase = 1)

β_i = parameter explaining how each variable affects μ (All parameters can be found in the β_i column in Table 3)

I(X) = indicator function for variable X

$$\text{Example: } I\,(site = 1) = \begin{cases} 1\ if\ location = 1 = EZ \\ 0\ if\ otherwise \end{cases}$$

Table 3. Parameters ($\widehat{\beta\iota}$), standard errors, and p values for each term in multiple regression linear model 1

Term	$\widehat{\boldsymbol{\beta\iota}}$	**Std.Error**	**Pr(>|t|)**
Intercept	59.586	2.954	< 2e-16
Site1 (EZ)	5.532	2.392	0.02089
Rugosity2	-2.147	2.374	0.36599
Rugosity3	-8.638	2.865	0.00262
Rugosity4	-16.384	3.685	9.47e-06
GFBrain	-59.383	9.028	6.88e-11
GFCaespitose	11.403	2.606	1.31e-05
GFCorymbose	-25.729	2.785	< 2e-16
GFDigitate	-21.865	3.217	1.62e-11
GFEncrusting	-56.591	2.628	< 2e-16
GFGolfball	-45.618	4.130	< 2e-16
GFHoneycomb	-33.105	7.196	4.62e-06
GFMushroom	-58.910	9.967	4.34e-09
SpringPhase1	20.447	2.575	4.24e-15

Model B

Final form of the multiple regression linear model that was used for growth form and spring phase data predictions.

$$\mu = \beta_0 + \beta_1 I(gf = brain) + \beta_6 I(gf = caespitose) + \beta_2 I(gf = corymbose) + \beta_3 I(gf = digitate) + \beta_4 I(gf = encrusting) + \beta_5 I(gf = golf\ ball) + \beta_6 I(gf = honeycomb) + \beta_7 I(gf = mushroom) + \beta_8 I(springphase = 1)$$

Where:

μ = predicted bleaching severity

gf = growth form

spring phase = before the April 21st, 2019 low spring tide (spring phase = 0) or after the April 21st, 2019 low spring tide (spring phase = 1)

β_i = parameter explaining how each variable affects μ (All parameters can be found in the β_i column in Table 3)

I(X) = indicator function for variable X

$$\text{Example: } I\ (springphase = 1) = \begin{cases} 1\ if\ springphase = 1 = after \\ 0\ if\ otherwise \end{cases}$$

Table 4. Parameters ($\widehat{\beta\iota}$), standard errors, and p values for each term in multiple regression linear model 2

Term	$\widehat{\beta\iota}$	Std.Error	Pr(>|t|)
Intercept	61.890	1.934	< 2e-16
GFBrain	-60.575	9.086	3.83e-11
GFCaespitose	12.157	2.599	3.21e-06
GFCorymbose	-26.508	2.771	< 2e-16
GFDigitate	-23.095	3.227	1.37e-12
GFEncrusting	-58.032	2.485	< 2e-16
GFGolfball	-46.998	4.093	< 2e-16
GFHoneycomb	-34.448	7.201	1.91e-06
GFMushroom	-62.282	10.006	6.48e-10
SpringPhase1	13.011	1.727	9.16e-14