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A Disappearing Island:
An Impact Assessment of Coastal Erosion on the Mnemba Island House Reef, Zanzibar

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SIT Zanzibar, Tanzania: Coastal Ecology and Natural Resource Management
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Abstract

Sedimentation is one of the greatest threats reefs face today due to climate change-induced sea level rise. Mnemba Island has experienced rampant coastal erosion as a combined result of global processes and local anthropogenic impacts, which has in turn caused severe reef degradation. The house reef was surveyed over a 3-week period to determine the amount of sediment deposited on the reef and the impact of this sedimentation on coral reef health. Sediment traps were deployed to measure the sediment flux rate. The line-intercept transect method was used to measure the benthos cover of the reef and point-transect method was used to measure the relative sediment cover of the substrate. Counts of indicator fish species (*Scaridae, Balistidae*, and *Siganidae)* and echinoderm (*Echinoidea* and *Acanthaster planci)* species were counted using the belt transect method. Overall, the reef exhibited very poor health that calls for urgent attention. Sediment flux rates on the reef are close to the lethal limit, potentially impacting algal growth. The reef is comprised of a low percentage of live coral cover and few herbivorous fish species. Furthermore, much of the reef is overtaken by *Echinoidea.* These findings suggest that sedimentation is a primary cause of reef degradation in conjunction with significant and direct anthropogenic impacts. Current erosion mitigation practices are not sufficient to adequately protect the shoreline. Recommendations for urgent protection of the island and its reef are discussed.

Muhtasari

Mzunguko wa Changarawe ni moja kati mabo yanayosababisha madhara kwa matumabawe siku hizi kutokana na tabia nchi – na kupelekea kupanda kwa ujazo wa bahari. Kisiwa cha Mnemba kinakabiliwa mmomonyoko mbaya wa mwambao wa bahari kutokana na mchanganyiko wa matokeo ya mabadiliko ya dunia na matendo yanayoleta athari yanayofanywa na wenyeji, yanayopelekea kusababisha uharibifu wa matumbawe .Mwamba wa “ house reef” ulifanyiwa uchunguzi kwa muda wa wiki tatu (3) kuweza kujua kiwango cha changarawe kinachoganda kwenye matumbawe na athari ya changarawe kwa maisha ya matumbawe. Mitego ya “sediment traps” iliwekwa ili kupima kima cha changarawe . Njia ya “line-intercept transect” ilitumika ili kupima viumbe vya baharini vinavyoishi juu au chini ya maji bahari na kufunika matumbawe na njia ya “point-transect” ilitumika kupima wastani wa changarawe il kufunika mahali ambamo viumbe vya bahari vinaota, vinaishi, vinakua na kupata mahitaji yao. Kuhesabu alama za samaki waonesho ubora wa mwamba (*Scaridae, Balistidae,* and*Siganidae)* and echinoderm (*Echinoidea* and *Acanthasterplanci)* aina zaviumbe hawa ilitumika njia ya “belt transect”. Kwa ujumla, Mwamba unaonyesha hali si nzuri , kwa haraka na juhudi zinahitajika. “Sediment flux” rates katika juu ya mwamba ipo karibu na ukanda wa hatari , kwa ujumka inaathiri ukuwaji awa mwani . Mwamba una asilimia ndogo ya matumbawe na samaki wachache wanaokula majani. Ukiomgezea , matumbawe mengi yamechukuliwa na “*Echinoidea”*Matokeo haya yananaonyessha . Matokeo haya yanaonyesha changarawe zinaweza kuwa kuwa ni chanzo cha uharibifu wa matumbawe pamoja na harakati za wanadamu na athari zake mkakati wa kupunguza mmomonyoko wa udongo na kwa sasa hautoshelezi na hatua za haraka za kuzuia ufukwe zinahitajika. Ushauri kwa kwa uharaka , ili kukilinda kisiwa zimetolewa na zimeelekeza.

Introduction

The eastern coastline of Mnemba Island is eroding at a shocking rate of five meters per year. With this destruction comes the degradation of its house reef. Sediment is removed from the shoreline and eventually deposited on the reef, where it has the potential to drastically alter the ecosystem. Although the Mnemba Island house reef faces a slew of anthropogenic and environmental threats, heavy sediment deposition from the eroding shoreline is a principal factor in its deterioration. This study aims to measure the extent of this damage by quantifying the sedimentation rate on the reef and assessing sediment-induced health impacts on the coral reef ecosystem. A comprehensive study was conducted in 2016 of the physical oceanography and coastal erosion on Mnemba Island. Prior to this, wave and sediment transport information on Mnemba Island had not been documented (Swanepoel, 2016). The research was critical in determining the local oceanographic character and the factors driving extreme coastal erosion. The crucial next step, however, is to ascertain the biological implications of findings.

Mnemba Island will serve as a case study to determine the effects of sediment deposit on coral reefs, an issue critical to understand as a pressing issue for reef health at a global scale. Sea level is rising at a rate faster than it has in the past 2100 years (Kemp et al., 2011). Low-lying islands and their surrounding reefs are particularly susceptible to these threats, as exemplified by the rapid erosion of Mnemba Island. Mnemba is a tropical paradise well-worth saving. It is a biodiversity hotspot that supports a rich tapestry of terrestrial and marine species, some of which are endangered. Like other oceanic islands, it also acts as a natural laboratory for scientific discoveries and innovations (Kueffer and Kinney, 2017). Furthermore, the island generates revenue for the country as a popular tourist destination and its marine fish stocks play a role in support of the local community. However, this is all threatened by the rapid corrosion of the island's coastline. In a number of years, these ecological and economic services may disappear. Therefore, monitoring of the erosion and its impact on the coral reef is crucial to identifying the most effective conservation measures moving forward.

Background

The key concepts involved in the study are reviewed followed by an overview of the geological history of the study location. Past and current erosion mitigation practices at the study site are also briefly discussed.

Coral Reefs

Coral reefs are complex 3-dimensional calcareous structures built up by biological activity that are home to some of the most diverse ecosystems in the world (Muhando, 2017). Coral lives in a symbiotic relationship with zooxanthellae, single-called photosynthetic algae (Richmond, 1997). Coral receives photosynthetic products and enhances its calcium metabolism from the algae, while the algae in turn benefits from protection and nutrients (Muhando, 2017). Coral reefs need sunlight, warm temperatures, ample salinity (over 20 ppt), and relatively sediment-free and low-nutrient water to grow (Lieske and Myers, 1996). The complexity of the coral structure provides niches for a variety of fish, crustaceans, gastropods, echinoderms, and numerous benthic organisms (Richmond, 1997). Coral reef health has become a pressing topic in recent decades as coral reefs have declined by 50% in the last 30-50 years. Thirty percent of coral reefs are anticipated to disappear globally during the next 30 years in the face of climate change (Burke et al., 2011). This projection has significant implications for coastal communities and for the Western Indian Ocean region as a whole, where 21.6% of the global tropical coral reef area is found (Burke et al., 2011).

Coastal Erosion

One of the direct consequences of climate change-induced sea level rise is a predicted increase in coastal erosion (Mustelin et al., 2009), the net loss of sediment from the shoreline (Mzee, 2018). Rising sea levels enable higher waves to reach the shoreline, increasing the size and frequency of waves on the coast which exacerbates erosion (Bird, E.C.F., 1996). Erosion can also occur on shorelines where the sea level is stable or even falling (Bird, 1996). Erosion is a natural part of the dynamic change at shorelines, but anthropogenic influences can significantly increase erosion. Coastal development, beach use, and devegetation destabilize the shore, while sand mining, mangrove cutting, and motorized activity can directly affect the amount of sediment available for the coast (Pitman, 2014). Although there is a law in Zanzibar prohibiting construction within 30 meters of the shoreline, it is rarely adhered to (Mustelin et al., 2009). Field signs of erosion include uprooted trees, wave undercut cliffs, collapsed cliffs, the presence of protective structures, beach berms and scarps, and a flat beach slope (Mzee, 2018).

While it is impossible to completely stop erosion, there are measures that can be taken to significantly hinder its magnitude and rate. Erosion mitigation structures are generally separated into two different engineering categories: hard structures are human-made structures rock, cement and concrete. Soft structures are an ecological approach to erosion mitigation and constructed out of natural materials (Mzee, 2018). More information on specific structures can be found in Table 7 in the appendix.

Coastal Erosion and Coral Reefs

One of the most important ecological services provided by coral reefs is the absorption of wave energy, thus protecting shorelines from enhanced wave impacts. The reefs act as a natural barrier to storm surges and can attenuate wave energy by up to 97% (Ferrario et al., 2014).

Bathymetry plays a key role in this process; shallower reefs absorb wave energy more effectively than deeper reefs (Ferrario et al., 2014). Degraded coral reefs exhibit less friction, allowing larger and stronger waves to reach the shoreline more frequently (Swanepoel, 2016). It is projected that by the mid-century, climate change and anthropogenic influences will degrade coral reefs so much that there will be net erosion on global coastlines (Yates et al., 2017).

On the other hand, coastal erosion also has a significant impact on coral reefs; it enhances sediment suspension and deposition (Ogston and Field, 2010). Sedimentation is one of the greatest threats that reefs face (Rogers, 1990). Large loads of sediment force the coral to increase its respiration rate, energy that should be used for necessary processes like reproduction and growth. Overall colony fitness decrease as a result (Gleason, 1998). In extreme cases, large sediment loads of inorganic particles can cause smothering and tissue death (Gleason, 1998). Sediment loads on coral can also interfere with the photosynthetic processes of the zooxanthellae, causing bleaching (Ogston and Field, 2010).

History of Accretion and Erosion on Mnemba

Mnemba Island experienced significant growth in 1973 after the introduction of the invasive *Casuarina* trees expanded the island eastward (Swanepoel, 2016). Although the *Casuarina* initially caused island growth, they eventually created an imbalance in the natural forest ecosystem (Swanepoel, 2016). Furthermore, the eastern shoreline was opened up to enhanced wave impacts when much of the fringing reef surrounding the eastern side of the island was compromised (Gibor, personal communication, 2018). Due to the terrestrial impacts of the *Casuarina* and the enhanced wave action from the compromised coral reef, the island stopped growing and started to steadily erode in the middle 1990s (Swanepoel, 2016). Figure 3.2 captures the initial growth of the island and its subsequent recession until the present day. Today, the island continues to recede at an alarming rate of four to five meters per year (Swanepoel, 2016).

Figure 1. The vegetation line in 2011 shifted significantly westward since 2004. (S. Rattray)

The increased erosion on Mnemba has resulted in serious impacts to the island's environment and infrastructure. The eastern shoreline of Mnemba is littered with fallen trees lying perpendicular to the shore. They may be further aggravating the erosion by increasing the turbulent zone and loosening the sediment upon impact (Swanepoel, 2016), although other literature points to the efficacy of shoreline debris in sand stabilization (Mustelin et al., 2009). In July 2017, the wave impact was so severe that a coral brick building used for staff housing on the east shore was completely wiped out, the remnants of which still remain on the beach (Gibor, personal communication, 2018). The new staff quarters constructed after the original building was destroyed is already in danger of the same fate, prompting discussions of moving employee housing to the mainland of Unguja Island in the future (Raaths, personal communication, 2018).

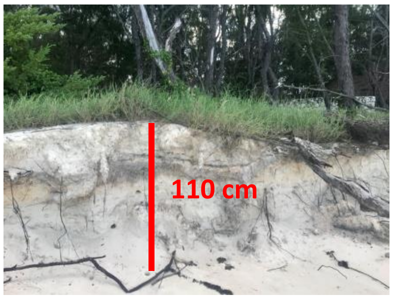
A steep beach scarp measuring as high as 1.1 meters runs along the eastern shoreline. There are large areas of exposed roots and the scarp is severely undercut by excessive wave action.

Several past unsuccessful attempts have been made by Mnemba employees to protect the shoreline. Woven sugar and grain bags were stacked along the beach to absorb the wave impacts, but were quickly wiped out by the falling trees (Swanepoel, 2016). More recently, in 2017, Mnemba employees initiated a re-vegetation project, referred to as "The Sapling Project", in an effort to increase vegetation cover and to slow the erosion (Programme for Mnemba Rehabilitation and Nursery Establishment, 2016). Although officials from the Forestry Department periodically visit Mnemba to inspect the erosion, no possible solutions have been offered and nothing has been done to aid the island in erosion mitigation (Gibor, personal communication, 2018).

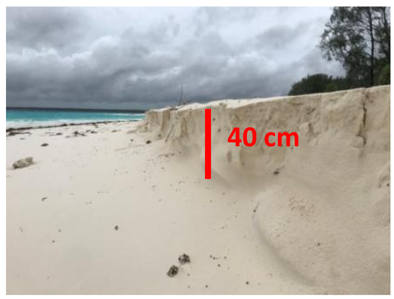
(a)

(b)

(c)



(d)



(e)

(f)

Figure 2. Impacts of erosion on Mnemba Island as of April 2018. (K. Grellman) (a) Row of fallen trees along eastern shoreline. (b) Remnants of the staff quarters that were destroyed by wave impact. (c) An uprooted tree on the eastern shoreline. (d) The steep scarp along the shore is evidence of significant erosion. (e) The scarp along the northern shore of the island is significantly smaller than that on the eastern shoreline. (f) The scarp is undercut by wave activity on the eastern shoreline. (g) Photo locations indicated by letter of photo.

(g)

Study Area

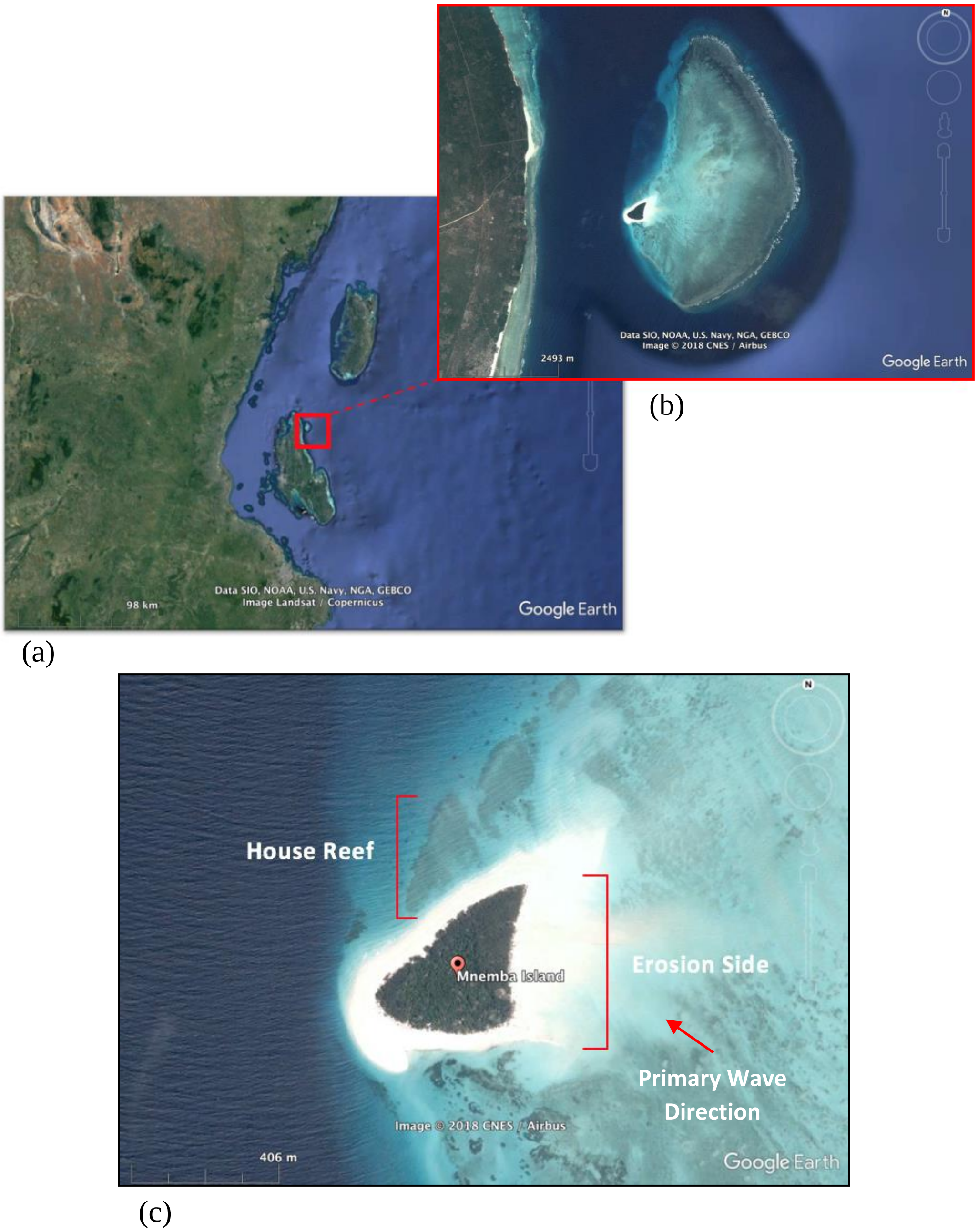


Figure 3. Map of the study area. (a) Zanzibar Archipelago. (b) Mnemba Island and the surrounding fringing reefs. (c) Notable locations on the island pertaining to the study.

Mnemba Island (S 05° 49.218'E 039° 22.959') is a small private island located 4.5 kilometers off the northeastern coast of Unguja Island and opposite Muyuni Beach. The island is a part of the Zanzibar Archipelago in the Western Indian Ocean. It is currently leased by the luxury travel company &Beyond that runs a resort on the island called Mnemba Island Lodge. Mnemba has a circumference of 1.5 kilometers and an approximate area of 11 hectares (&Beyond Website). It is characterized by a humid tropical climate with a mean annual maximum temperature of 29.3°Celcius and a mean annual minimum temperature of 21.2°Celcius. The East African Coastal Current (EACC) is the dominant current in the region. It runs permanently northward with a net velocity of two knots (Nyandwi, 2018). There are two monsoon seasons each year: the northeast monsoon season (*kaskazi)* lasts from November to March and experiences strong winds, thus accelerating the EACC and significant beach erosion; the southeast monsoon season (*kusi)* lasts from June to September and is characterized by beach accretion on Mnemba Island (Mustelin et al., 2009). Annual rainfall varies, with long rains (*masika)* occurring from March to June and short rains (*vuli)* occurring from October to December (Mustelin et al., 2009).

Mnemba is a low lying island, meaning it rises less than four meters above sea level. As a result, the beach profile is highly dynamic and changes dramatically with the conditions and the four meter tidal variation (Swanepoel, 2016). The beaches are composed of fine-grained sand, leaving them particularly susceptible to erosion due to ease of sediment transport (Pitman, 2014). The primary wave direction comes from the southeast of the island and moves northward (Swanepoel, 2016). Sediment is carried in high concentrations in the water column along the eastern border of Mnemba Island and accretes on its northeastern lip (Swanepoel, 2016), thinning out the island and forming a long northern-extending arc.

The Mnemba Island Marine Conservation Area (MIMCA) was established in November 2002 (Nangle and Sheng, 2010). There is no fishing allowed within 200 meters of the island

(Rattray, personal communication, 2018). It hosts a variety of endangered species, including Aders's duikers (*Cephalophus adersi)*, suni antelopes (*Neotragus moschatus)*, coconut crabs (*Birgus latro)*, and green sea turtles (*Chelonia mydas)*. Off the east coast, a fringing reef surrounds the island that stretches roughly seven kilometers from its top to bottom point (Swanepoel, 2016). Seagrass beds are the dominant marine ecosystem on the southern side of the island. The house reef (S 5° 43'00.0) is a small fringing reef, roughly triangular in shape, located on the northern shore of the island with an estimated area of 0.25 kilometers^2 and a maximum depth of 7 meters. This study was conducted at the house reef over an 18-day period from April 6th to April 23rd during the *masika* rains and *kusi* monsoon season.

LOW TIDE	**HIGH TIDE**
 (S 5° 49' 6.013"E 39° 23' 6.915")	

 (S 5° 49' 6.026"E 39° 23' 8.228")	
 (S 5° 49' 10.241"E 39° 23' 5.983")	
 (S 5° 49' 20.019"E 39° 23' 1.472")	

Table 1. Pictures taken at low and high tide on various parts of the island show the dramatic transformation of the beach profile. Low tide pictures taken on 14/04/18 at 9:30am, tide 0.55 meters. High tide pictures taken on 13/04/18 at 3:00pm, tide 3.32 meters. (K. Grellman)

Methodology

An interdisciplinary approach was taken to assess the health of the Mnemba Island house reef with a specific focus on the impacts of sedimentation. Both geological and biological indicators were studied to measure the sediment coverage in relation to the overall reef health. In addition, informal interviews were conducted with various Mnemba employees to learn more about the history of the island.

Reef Benthos Sediment Coverage

Prior to the study, the researcher developed a zero to five rating scale for the relative amount of sediment coverage on reef benthos. A preliminary survey was conducted to practice using the scale for enhanced consistency and accuracy throughout the study. The standard point-intercept transect (PIT) method was used to determine the sediment coverage level at every five-meter mark along the transect line (English et al., 1994). At every point, a 0.5 by 0.5 meter quadrat was placed over the substrate. The sediment coverage was only rated if the substrate was not sand and rose at least five centimeters from the sea floor.

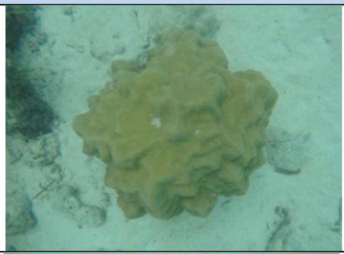
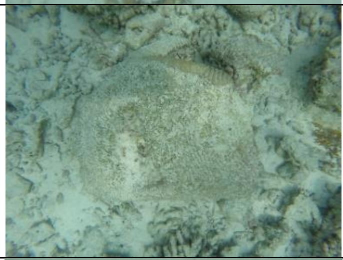
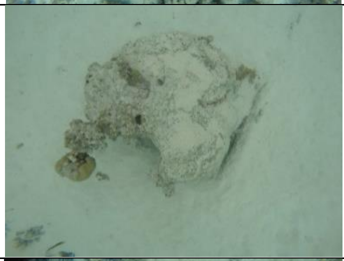
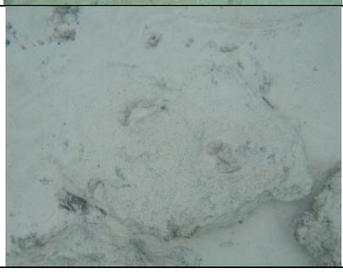
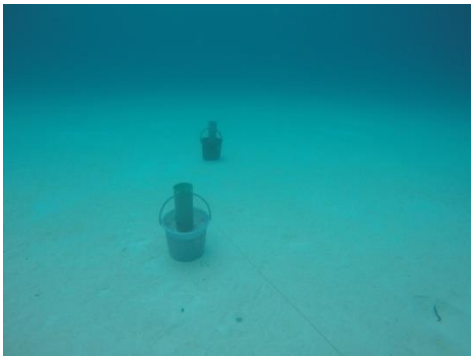
Rating	Reference Picture
0 – No coverage.	
1 – Minimal coverage.	
2 – Light coverage.	
3 - Moderate coverage.	
4 – Heavy coverage.	
5 – Full coverage.	

Table 2. Sediment rating chart used as a reference throughout the study.

Sedimentation Rate

(a)

(b)



(c)

Figure 4. Images of sediment traps and the station locations. (a) Sediment trap station locations. (b) Sediment trap A at Station #4 (S 5° 48' 54.18"E39° 23'7.544"). (c) Sediment traps A and B at Station #3 (S 5° 48' 57.661"E39° 23'1.438"). Both photos taken on day of deployment (13/04/18). (K. Grellman)

Nine sediment traps were deployed to estimate the vertical sediment flux in and around the house reef. Traps were constructed by an artisan from the Institute of Marine Science (IMS) in Zanzibar using PVC pipes, flower pots, funnels, and cement (Muzuka et al., 2010). The internal diameter of each trap was 11 centimeters and the length was 55 centimeters, for a diameter: length ratio of 1:5 (Muzuka et al., 2010). The traps were deployed on April 13th at 9:30am during low tide to ensure that they were placed at a water depth of at least five meters (Shaghude, personal communication, 2018). There were five permanent sediment trap stations. Two traps were deployed at each station spaced one meter apart for reproducibility, with the remaining trap placed solo in the fifth and farthest station from the reef (Storlazzi et al., 2011). Three of the stations (#1-3) were arranged in an arc around the reef to measure the amount of sediment being deposited on the coral, while the remaining two stations (#4 and 5) were placed northeast of the reef closer to where the initial sediment suspension from the eastern shore occurs. The sediment traps were checked weekly to ensure they remained in place and vertical. The sediment traps were retrieved after 18 days on April 30th. at 10:30am for a total deployment time of 433.5 hours. The collected sediment was dried for 48 hours. It was placed in an oven at a low temperature (<100 degrees Fahrenheit) for roughly 15 hours. Once the sediment was completely dry, it was weighed on a scale to record mass (g) and to calculate the sedimentation rate at each station (Muzuka et al., 2010).

Reef Benthos

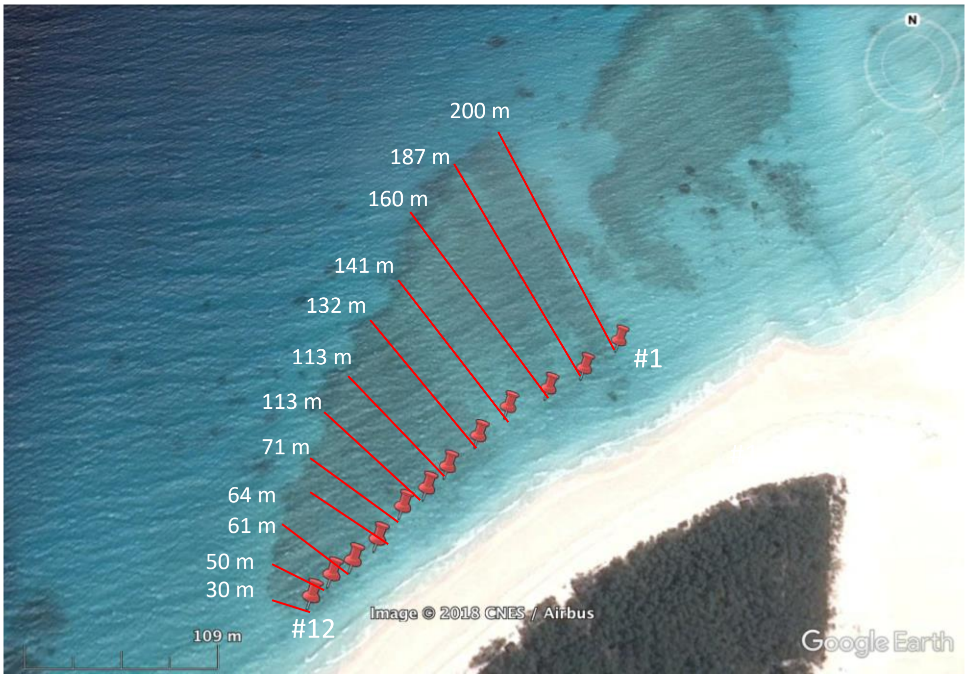


Figure 5. Approximate location of transect lines on the Mnemba Island house reef. Transect lines not to scale.

A preliminary visual survey of the study area was conducted on the first day of research to determine the number, length, and orientation of transects. The standard line-intercept transect (LIT) method was used to measure the percent cover of reef benthos (English et al., 1994). All transects were conducted during low tide. Twelve transects were laid perpendicular to the shoreline spaced 20 meters apart. The eastern-most transect (#1) was 200 meters in length and the western-most transect (#12) was 30 meters in length. Intermediate transects (#2-11) varied in length to cover the entire reef. The Global Positioning System (GPS) coordinates of the starting point of each transect line were recorded and translated to a map. The categories of reef benthos were predetermined to be: hard coral, soft coral, non-biotic (sand or rock), coral rubble, seagrass, dead coral, and “other” to remain consistent with a previous health assessment of the reef for enhanced comparability (Nangle and Sheng, 2010). Coral was identified to its generus (Gosliner et al., 1996). Coral stressors were noted under the following categories:

Bleaching ➢ Zooxanthellae living on the coral die, leaving behind the coral skeleton and resulting in lack of color and sometimes death. ➢ Linked to fluctuation in salinity levels, heavy deposits of sediment, toxins, and increases in ocean temperature. (Richmond, 1997).	 *Figure 6.* Bleached *Acropora*. (K. Grellman)
Lesions ➢ Areas of tissue loss and partial death (Nangle and Sheng, 2010). ➢ Could be the result of Crown-of-Thorns predation, bleaching events, or heavy sediment deposition (Muhando, personal communication, 2018). ➢ Common in shallow water reef communities (Muhando, personal communication, 2018).	 *Figure 7. Favia* showing lesions. (K. Grellman)
Algal Overgrowth ➢ Extreme algae cover on coral surfaces. ➢ Algal blooms can smother coral, causing abrasions and eventually death ("Algae," 2018).	 *Figure 8.* Unknown dead coralexhibiting algal overgrowth. (K. Grellman)

Table 3. Overview of environmental stressors that negatively impact coral reefs.

Throughout the surveys, a GoPro camera was utilized for photo-identification of any unknown coral genera, invertebrate species, and/or fish species. Genera and species were identified immediately following surveys.

Indicator Fish Species

The standard belt transect method was used to count indicator fish species (English et al., 1994): Parrotfish (*Scaridae)*, Triggerfish (*Balistidae*) and Rabbitfish (*Siganidae).* These species were chosen because they are top trophic predators of invertebrates (Triggerfish) and act as algal grazers (Parrotfish and Rabbitfish), helping to maintain a healthy coral reef ecosystem. Therefore, disappearance of these species could result in dramatic ecosystem shifts. The researcher waited five minutes after deploying the transect line to allow the fish to return to their regular biological behavior. A one meter T-stick was used to count any fish that fell within one meter on either side of the transect line. Fish were identified to their species level.

Parrotfish (*Scaridae)* ➢ Corallivores (feed on coral polyps). ➢ Maintain reef healthy by minimizing algae growth and feeding on sediment and coral tissue. (Mallon, 2010). ➢ Play a significant role in shaping coral reef substratum and producing beach sand (Lieske and Myers, 1996).	 *Figure 9.* Bullethead parrotfish (*Scarus sordidus).* (IUCNRedList.org)
Triggerfish (*Balistidae)* ➢ Omnivores (feed on coral polyps and invertebrates). ➢ Primary predators of invertebrates, including sea urchins and Crown-of-Thorns Starfish (COTS) (Mallon, 2010). ➢ Some species feed on live algae or zooplankton (Lieske and Myers, 1996).	 *Figure 10.* Halfmoon triggerfish (*Sufflamen chysopterus).* (FishBase.org)
Rabbitfish (*Siganidae*) ➢ Herbivores (feed on benthic algae). ➢ Help maintain healthy levels of coral algae. (Lieske and Myers, 1996). ➢ One of the primary roving "grazers" (Lieske and Myers, 1996).	 *Figure 11.* African Whitespotted rabbitfish (*Siganus sutor).* (AllFishes.net)

Table 4. Overview of surveyed fish species and their roles as bioindicators.

Echinoderms

Certain echinoderms that serve as bioindicators of reef health were counted using the standard belt transect method (English et al., 2010). The researcher swam along the transect line with a one meter T-stick and counted all sea urchins (*Echinoidea)* and Crown-of-Thorns Starfish (COTS; *Acanthaster planci,* both coral degraders, that fell within one meter on either side of the transect line. All echinoderms were identified to their species level.

Sea Urchins (*Echinoidea)* ➢ Herbivores (feed on coral algae), erode coral. ➢ In healthy levels, help maintain reef health by preventing macroalgae overgrowth.. ➢ Outbreaks can lead to unsustainable bioerosion of corals. ➢ Outbreaks linked to decline in predator species and/or depletion of food competition from disappearance of herbivorous fish (indication of fishing pressures) ("Urchins," 2018).	 *Figure 12.* Banded Urchin (*Echinothrix calamaris*). (K. Grellman)
COTS (*Acanthaster planci)* ➢ Corallivores. ➢ Prone to "outbreaks" in which they consume the coral faster than it can grow. ➢ Outbreaks linked to enhanced phytoplankton availability from nutrient runoff and decline in predator fish species ("Crown of Thorns Starfish," 2018).	 *Figure 13.* COT affixed to dead coral. (K. Grellman)

Table 5. Overview of surveyed echinoderm species and their roles as bioindicators.

Informal Interviews

A series of informal interviews were conducted with various members of the &Beyond staff on Mnemba Island and a MIMCA employee. Topics discussed include the history of the island, fishing restrictions and enforcement of these restrictions, erosion impacts on the island, measures taken to prevent erosion, and the past and current health conditions of the house reef at Mnemba Island. Details of individual interviews can be found in the appendix.

Results

A total of 1,322 meters of transect lines were surveyed on the Mnemba Island house reef. A preliminary visual survey clearly showed the extreme extent to which the reef is degraded.

Much of the coral – dead and live – was covered in layers of fine silt. Most of the coral was dead, and live coral often had lesions and showed signs of partial death. There was a relatively low abundance and diversity of fish species, and sea urchins dominated the reef. The overall reef health and sedimentation measurements are quantified in the figures below.

Sedimentation Rate

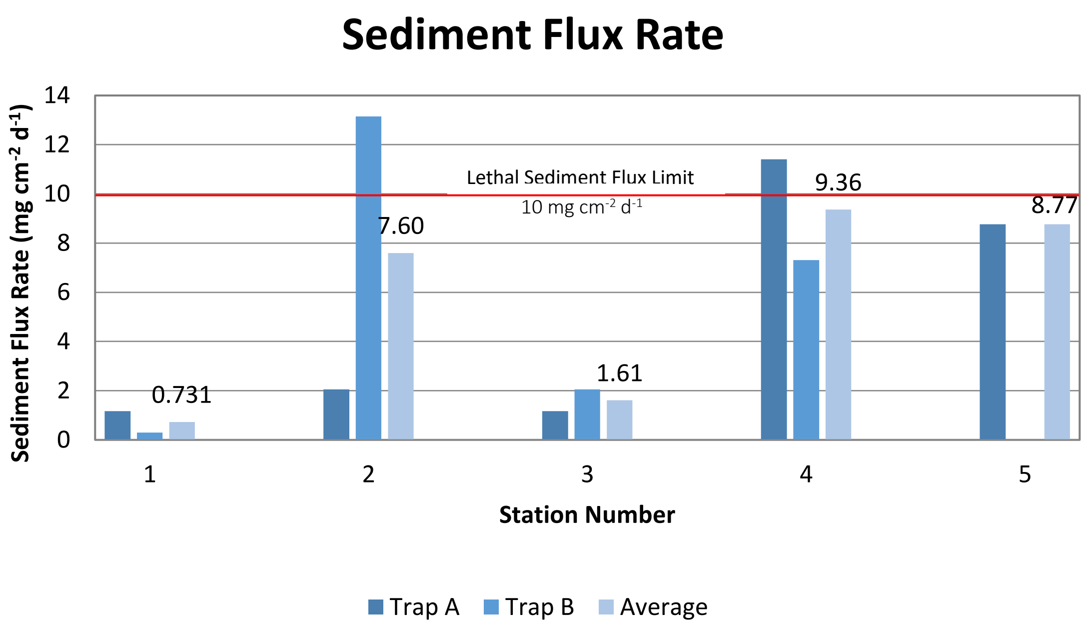


Figure 14. Sediment flux rates of each trap and the average at each station. Station #5 only had one trap deployed. The red line indicates the lethal sediment flux limit of 10 mg cm^{-2} d^{-1}.

The sediment flux rate at each station was variable. Station #1 exhibited the lowest sedimentation rate of 0.731 mg cm^{-2} d^{-1} followed by Station #3 with a rate of 1.61mg cm^{-2} d^{-1}. Station #1 is the farthest station from the erosion site and Station #3 is between two fringing reefs. Both of these values are well under the lethal limit of 10 mg cm^{-2} d^{-1} (Rogers, 1990), as indicated by the red line in Figure 6. Trap B at Station #2 measured a sediment flux well over the lethal limit of 13.15 mg cm^{-2} d^{-1}. Nevertheless, average sedimentation rates at #2 and #5 exhibit sedimentation rates that are only slightly under the lethal limit. Station #4 had the highest average (of both traps together) sediment flux rate of 9.36 mg cm^{-2} d^{-1}.

Reef Benthos Sediment Coverage

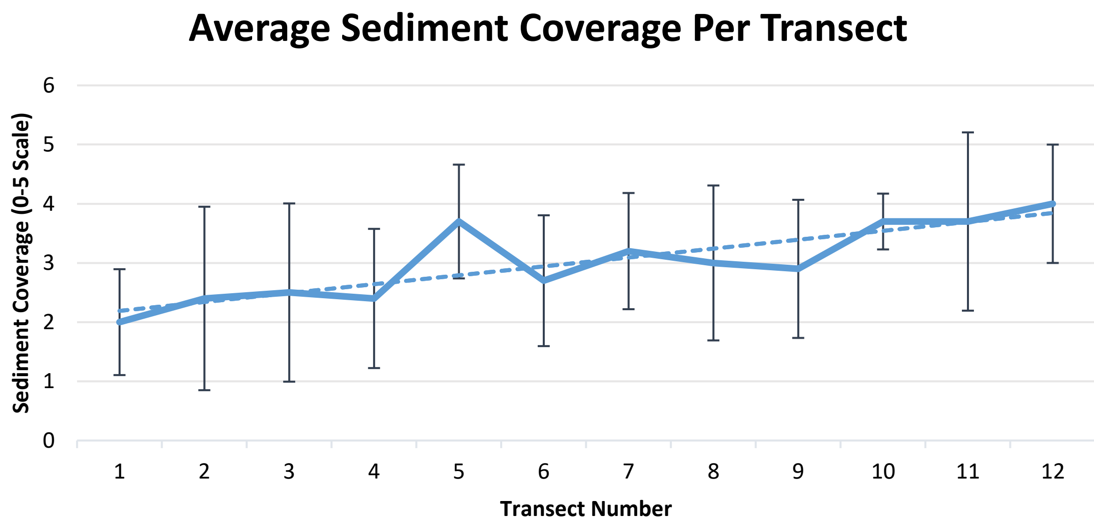


Figure 15. The average sediment ratings were taken for each transect. Transect #1 corresponds to the right-most side of the reef from the beach.

The overall average sediment coverage rating for the entire reef was 3.02 out of 5. There is a slight upward trend in sediment cover from transect line #1 to transect line #12, which corresponds to higher sediment coverage on the reef side farthest from the erosion side. However, the overlap of error bars is significant enough that the sediment coverage should be considered more or less consistent throughout the house reef.

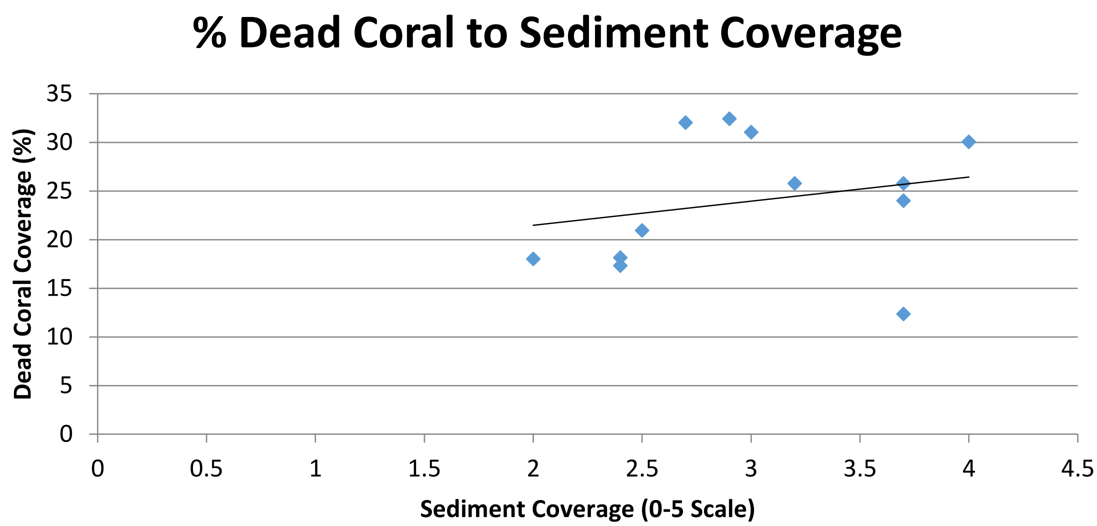


Figure 16. Correlation between the dead coral % and the average sediment coverage of each transect.

There is a loose correlation between the average sediment coverage and the percentage of dead coral cover for each transect line. The slight positive relationship between the measurements indicates that more sediment coverage contributes to enhanced coral death.

Reef Benthos Cover

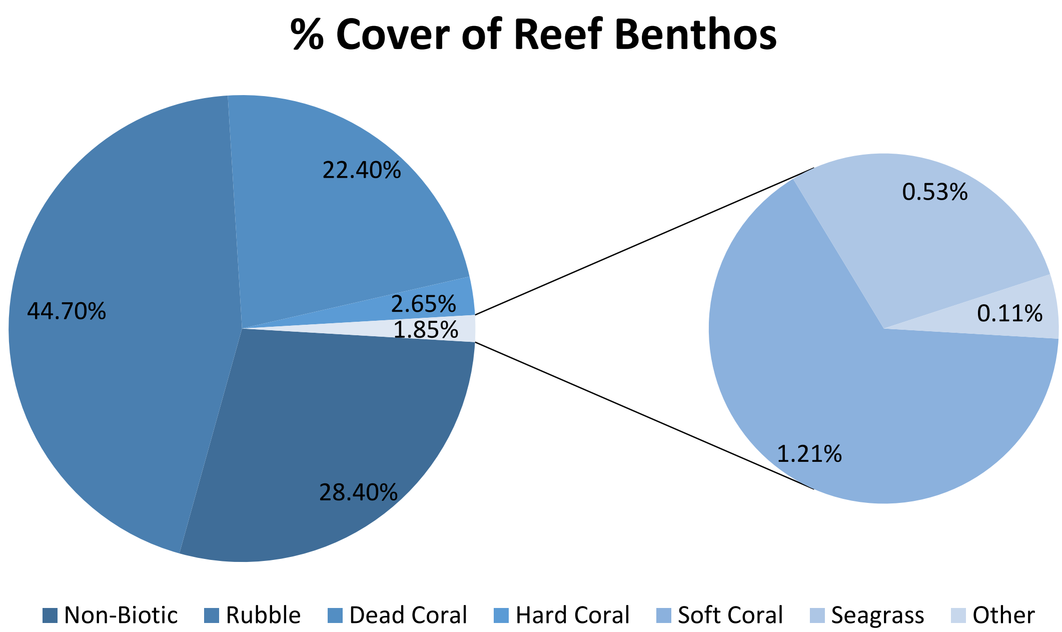


Figure 17. The percentage cover of each benthos category. “Other” refers to sea anemones (*Actiniaria)* and benthic organisms such as giant clams (*Tridacna gigas).*

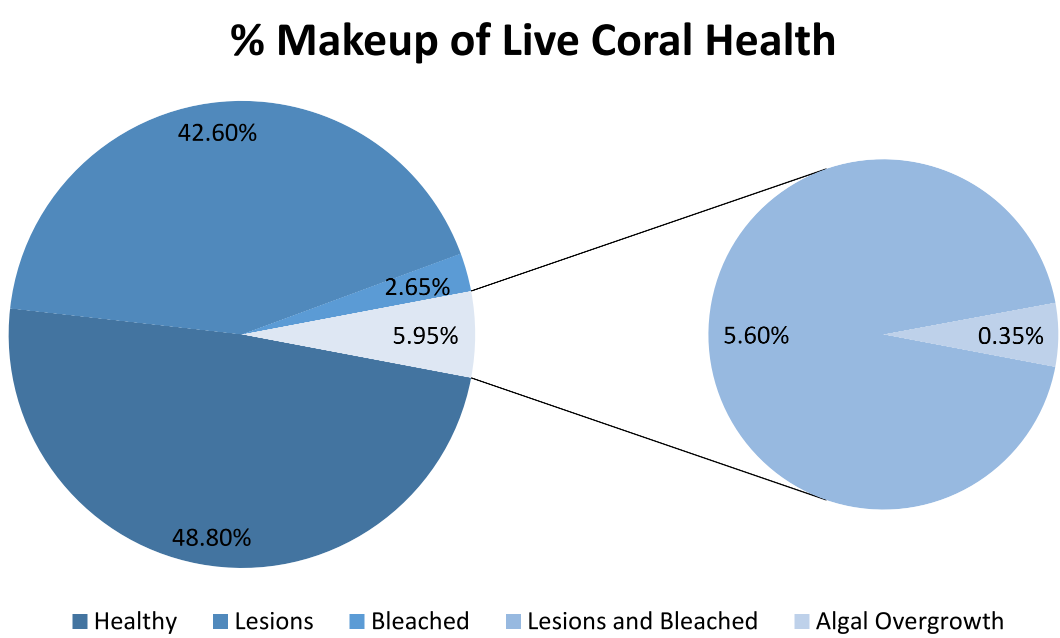


Figure 18. The percentage of live coral that was damaged versus undamaged.

Figure 17 shows that nearly half (44.70%) of the reef benthos makeup was coral rubble and almost a quarter (22.5%) of the coral was dead. The other dominant substrate was sand and rock (non-biotic), which amounted to nearly a third (28.40%) of the reef cover. Only 3.86% of the reef benthos was composed of live coral.

Figure 18 shows that a significant portion (48.20%) of the live coral had lesions, which is roughly the same percentage of live coral that did not show any damage (48.80%). Less than 1% of live coral exhibited signs of algal overgrowth and only 2.65% of the coral was bleached or partially bleached.

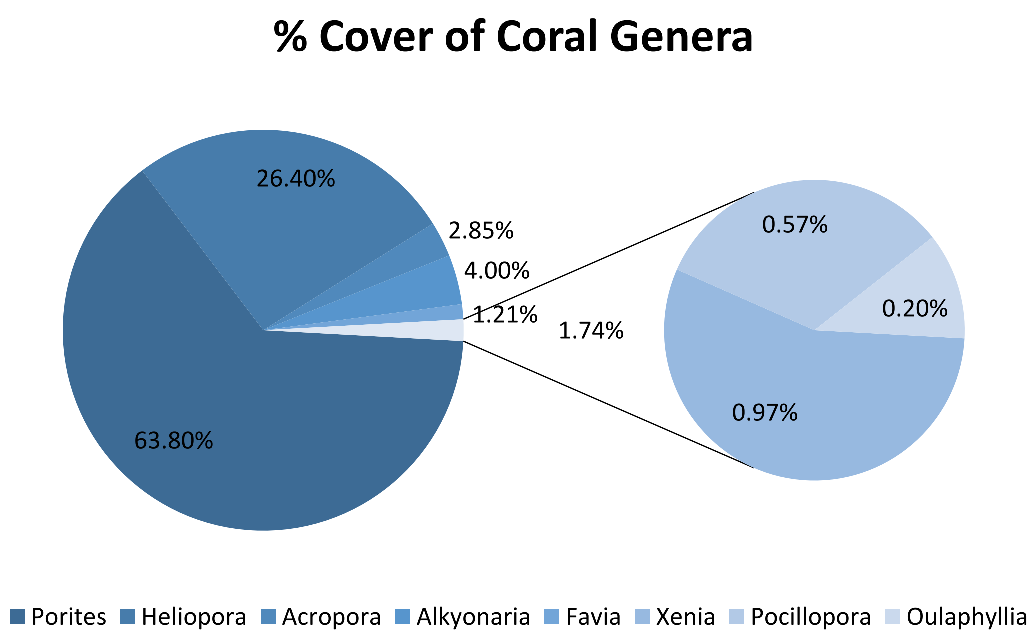


Figure 19. Makeup of coral genera observed in the reef.

A total of five genera of hard corals were observed (*Acropora*, *Porites*, *Favia*, *Pocillopora*, *Oulophyllia)* and three genera of soft corals were observed (*Heliopora, Xenia, Alkyonaria*). *Porites* spp., a hard coral, was the most dominant coral species in the reef followed by the soft coral *Heliopora* spp. Together, they made up 90.2% of the coral genera. Several small

Galaxea spp. colonies, a common stony coral found in the Indo-Pacific region, were also observed fairly regularly in the reef but were not accounted for in any of the transects.

Fish and Echinoderm Surveys

Class	Common Name	Scientific Name	Number of Individuals
Sea Urchin (*Echinoidea*)	Needle-Spine Urchin	*Diadema setosum*	1273
	Banded Urchin	*Echinothrax diadema*	1788
			Total *Echinoidea*: 3061
Starfish (*Asteroidea*)	Crown-of-Thorns Starfish	*Acanthaster planci*	4
			Total *A. planci*: 4

Table 6. Total number of sea urchins and COTS counted in the reef.

Sea urchins were extremely prevalent at the house reef. Only two different species were encountered. Of these, 58.4% were banded urchins (*Echinothrax diadema)* and the remaining urchins were the needle-spine variety (*Diadema setosum).* Over 3,061 total individual urchins were observed which amounts to roughly 2.3 urchins per meter of the total transected area. Only four total COTS were counted; however, visual observations of the house reef indicate that there is a higher prevalence of COTS than was observed along the transect lines.

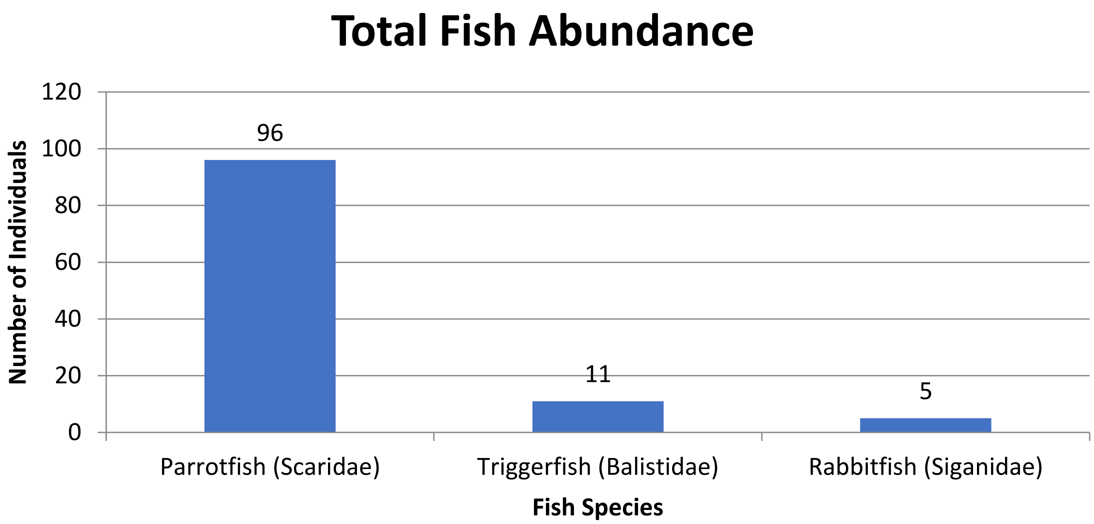


Figure 20. Total number of individual fish encountered per species. Parrotfish were the dominant fish species in the reef.

A total of 112 individuals of parrotfish, triggerfish, and rabbitfish were observed along the transect lines. Parrotfish accounted for 85.7% of the fish. Only 9.8% of the fish were triggerfish and the remaining 4.5% were rabbitfish.

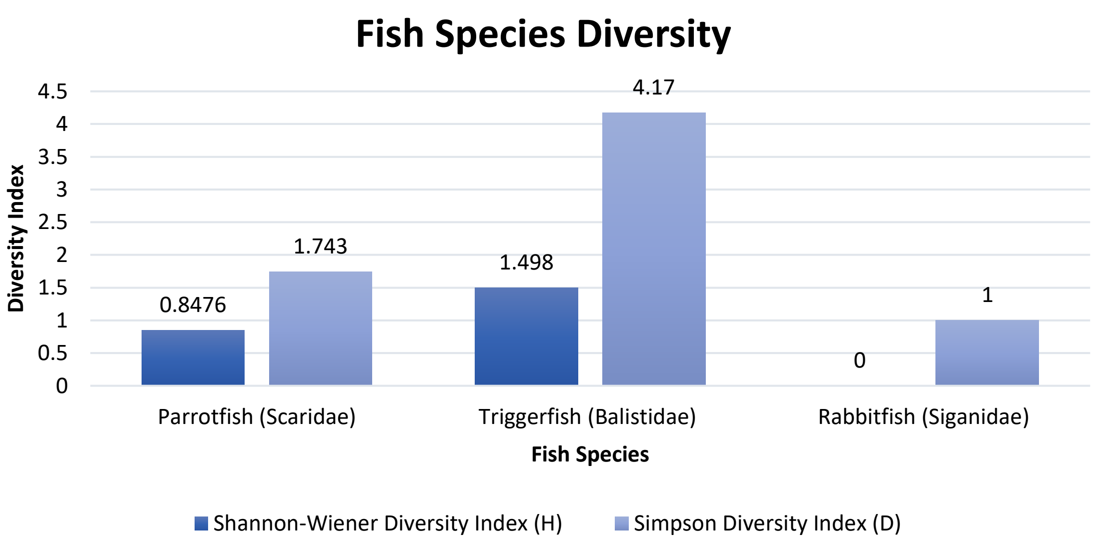


Figure 21. The diversity indices of each fish species for the entire reef were calculated.

The Shannon-Wiener Diversity Index and the Simpson Diversity Index account for the species richness (number of species) and the species evenness (abundance of each species) in a sample to measure the biodiversity of a given area. The Simpson Index gives more weight to dominant species, whereas the Shannon-Wiener Index assumes all species are randomly sampled and represented in a sample.

The diversity index of each fish species was relatively low. The common Shannon-Wiener Index range is from 1.5 to 3.5, and all Shannon-Wiener index for each fish species was below 1.5.There were five different species of parrotfish, five different species of triggerfish, and only one rabbitfish species observed during surveys. Counts of specific species can be found in Table 9 in the appendix.

Although a much higher abundance of parrotfish were observed than triggerfish (Figure 20), the diversity indices of parrotfish are lower than those for triggerfish because there was lower parrotfish species evenness. For instance, 71 of the 96 parrotfish individuals were of the same species (*Scarus sordidus)*. Rabbitfish exhibited the lowest diversity indices because only one species was encountered, which was accounted for in the dominance index (Simpson).

Discussion

The Mnemba Island house reef is dying at a shocking rate. Dive instructors who have worked at Mnemba for relatively short periods of time (Kooyman, 2 years; Makame, 11 months) said that the reef condition is significantly worse than it was when they first came to the island. Throughout their time on the island, these workers have experienced the visible destruction and death of the reef. A frequent diver at Mnemba Island around 15 years ago, Makame said he used to see large fish and sea turtles regularly. Now, charismatic creatures and large animals are a rare occurrence. The geological and biological indicators quantified in this study are consistent with these observations of the house reef degradation and provide further insight into the primary causes.

The implications of the geological health indicators will be discussed followed by an explanation of the biological health indicators. The effectiveness of current conservation and erosion mitigation strategies will be addressed after a discussion of the scientific findings, as the poor reef condition is evidence that the current practices are insufficient.

Figure 22. Dead *Acropora* table coral (approximate length two meters) in the house reef that was alive just two years ago. (K. Grellman)

Geological Indicators

The first research question of the study aimed to quantify the amount of sediment that is deposited on the house reef. The sediment traps suggest that sediment deposits on the reef at rates just under the lethal threshold limit (10 mg cm^{-2} d^{-1}). Trap #2B at Station 2 measured the highest sedimentation rate: 13.15 mg cm^{-2} d^{-1}. Station 2 traps were deployed directly at the fringe of the house reef and therefore provide the best evidence of the sediment that reaches the reef itself. The trap indicates that sediment is carried from the eastern side of the island to the northern shore, where the house reef is located, at a lethal rate. Its partner - trap #2A - measured a much lower sedimentation rate of 2.05 mg cm^{-2} d^{-1}. However, the latter was found dislodged seven days after deployment and therefore did not collect sediment for the entire deployment time. The two northern-most stations (#4 and #5) measured the highest average sedimentation rates of 9.36 and 8.77 mg cm^{-2} d^{-1}, respectively. This makes sense because they were placed in line with the wave direction and also are the closest to the erosion site. The trap deployed at station #5 was also found dislodged after seven days of deployment. Thus, it is safe to assume that the sediment flux rate is even higher than measured in the dislodged sediment traps.

In comparison, the traps at station #1 measured the lowest rates of sedimentation: 1.17 and .292 mg cm^{-2} d^{-1}. Station #1 is located behind the house reef, so the low sedimentation rate could be due to the fact that much of the sediment settled on the house reef before it reached station #1. As a general trend, the sites farther from the erosion area produced lower sedimentation rates. Station #1 is farthest from the eastern shoreline, which is consistent with this trend.

Station #3 was the exception to this trend; it measured a surprisingly low average sedimentation rate of 1.61 mg cm^{-2} d^{-1}. There are two possible explanations for this finding. The traps were placed between the house reef and the neighboring fringing reef, so much of the sediment may have been captured in the reefs before it reached these traps. In addition, station #3 traps were placed in the shallowest water of any station. For instance, when the traps were collected, these traps were in less than two meters of water, significantly below the suggested minimum water depth of five meters. Therefore, their ability to collect vertical sediment flux was likely somewhat hindered.

Analysis of the sediment particle size provides further insight into the impacts of sediment deposition on the coral reef. Weber et al. (2006) found that sediment size plays a critical role in coral stress. Finer-grained sediments are much more difficult for corals to shed.

All of the sediment collected in the traps was extremely fine silt (<1/16 mm). Therefore, the house reef is not only being impacted by lethal amounts of sediment, but also it is being impacted by a size class of sediment that is particularly stressful to the coral animals that constitute the reef.

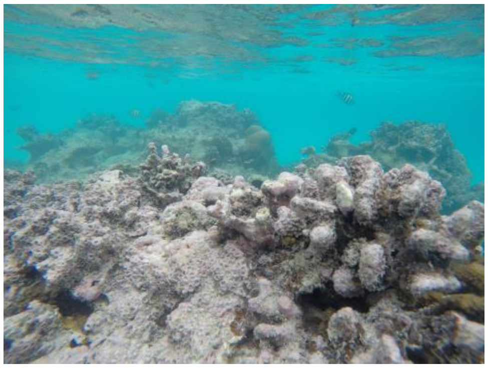
Although the sediment traps helped to quantify the amount of sediment deposited on the reef, there are important limitations to consider. The researcher only allowed two days for the sediment to settle and dry. Since the sediment was particularly fine, perhaps more time should have been allowed for the sediment to settle prior to pouring the water out of the individual traps. Some of the sediment was lost during the removal process so the calculated sediment rates are overly conservative figures. On another note, the use of sediment traps to measure sediment flux rates is somewhat contested in literature. Analysis of sediment trap uses shows that they are more effective when they measure suspended-sediment dynamics than deposited sediment (Storlazzi et al., 2010). Nevertheless, heavy suspended particle loads at coral reefs still block sunlight and disrupt photosynthetic processes, which cause stress to corals. Due to the time constraints of this study, the calculated sediment rates are only representative of a certain time of the year. The rates are likely to vary with the changing seasons and wind patterns. Therefore, deployment of sediment traps during different seasons and for longer periods of time is strongly recommended for further study.

In addition to the sediments captured in the traps, a high rate of sedimentation was noticeable due to the thick layers of sediment that covered much of the study area substrate. The average sediment coverage rating (Table 2) for the reef was 3.02: moderate coverage. However, the average sediment coverage for transect line #1, the closest transect to the erosion site, was a 2 (light), while the average coverage for transect line #12, the farthest transect, was a 4 (heavy).

This contradicts the trend of sedimentation rates in which there is more sediment deposited in northern regions of the shore that are closer to the original site of erosion. There are a few possible explanations for this. The sediment could be initially caught on the northern side of the reef and eventually make its way, through wave action, to the opposite side of the reef where it builds up. In addition, the northern side of the reef was characterized by more coral rubble. The sediment is more likely to be caught in larger pieces of coral that characterize the southern side of the reef as compared against the other sides of the reef. However, there are instances in which this trend does not apply. For transect line #5, for example, the average sediment coverage was 3.7 (moderate/heavy), while transect line #4 had an average rating of 2.4 (light/moderate) and transect line #6 had an average rating of 2.7 (light/moderate). Transect line #5 was conducted during a day of strong winds and high turbidity. As a result, the amount of suspended particles in the water was significantly higher than other days, possibly an impactful factor on the sediment coverage rating. This shows the limitations of applying a subjective scale to sediment coverage. It is also important to highlight the fact that most of the sediment ratings per transect line were highly variable, with most standard deviations greater than 1. Therefore, it is appropriate to conclude that the sediment coverage is more or less uniform throughout the study area.

As regards to another key piece of evidence, the percentage of dead coral cover is somewhat correlated to the sediment coverage. For example, transect line #11 had an average coverage rating of 3.7 (heavy) with dead coral comprising 25.79% of the benthos cover, while transect line #2 had an average coverage rating of 2.4 (light/moderate) with dead coral comprising only 17.32% of the benthos cover. However, there are discrepancies, such as along transect line #10. The average sediment coverage rating there was 3.7 (moderate/heavy), but the overall percentage of dead coral cover was only 12.37. There were only three measurable sites for sediment cover on transect #10 because the amount of non-biotic substrate was much higher relative to the other transect lines, so the sediment rating may not be representative of the entire area. This discrepancy highlights the limitations of the PIT method for measurement of sediment coverage.

Of the live coral, a significant portion of it (48.55%) was damaged from lesions and, in total, only 48.80% was healthy. It was common to observe colonies of coral, particularly of *Porites* spp., that were healthy on the sides but sediment-filled and partially dead on their tops and in their centers. Corals with concave portions had a harder time shedding sediment, so the build-up of fine silt could have caused anoxia and lesions (Weber et al., 2006). These lesion patterns can also be attributed to the shallow water environment that characterizes a majority the house reef. The center of the reef experiences substantial variations in water depth due to the relatively large tidal range, while the outer edge of the reef is on a drop-off and therefore in deeper water. The center of the reef was comprised of mostly dead or lesioned coral with minimal 3-D structure, whereas the edges of the reef exhibited larger areas of complex coral structure. Although the coral along the outer edges of the reef appeared healthier, in fact most of the coral was dead despite the well preserved coral skeletons. Eventually, these skeletons will break down like the rest of the reef.


(b)


(b)

Figure 23. Coral along the edge of the reef versus in the center of the reef. (a) Although there is more complexity to the coral structures on the edge of the reef, most of it is already dead. (b) The middle of the reef is characterized by coral rubble and dead coral that has largely lost its structural form. (K. Grellman)

There was a very low abundance of healthy coral affected by algal overgrowth. Only 0.35% of the coral exhibited unhealthy levels of algae. This is consistent with prior studies done on sediment impacts to coral reefs, in which sites heavily influenced by sediment deposition had lower overall algal abundance (McClanahan and Obura, 1996). Although in some instances nutrient-rich sediment can cause algal blooms (Weber et al., 2006), the lack of algae at the house reef suggests the deposited sediment is not high in nutrients. Detailed analysis of the particle make-up would be beneficial as a future study. Weber et al. (2006) also found connections between sedimentation on corals and their bleaching. In their study, some corals that initially appeared unaffected by sediment exhibited bleaching within two days of sediment removal, possibly due to anoxia of zooxanthellae. Furthermore, within four days of sediment removal, the coral still had not fully recovered from sedimentation stress. This has substantial implications for the house reef corals that receive large loads of sediment deposit on a regular basis.

The coral genera make-up of the house reef also determine the degree of sedimentation impact. Different types of coral vary in their sedimentation tolerances (Gleason, 1998). The most common coral genus of the reef was *Porites*, which is considered to have an intermediate sedimentation tolerance (McClanahan and Obura, 1996). *Acropora*, the fourth most abundant genus on the reef (2.85%), has intermediate tolerance (McClanahan et al., 1996). *Favia* and *Pocillopora*, which comprise 1.21% and .57% of the reef, respectively, are largely intolerant of sedimentation (McClanahan and Obura, 1996). The only coral observed on the reef considered sediment-tolerant was *Galaxea*, although it was not represented in any transect lines possibly due to its wide spatial distribution. Very few of the *Galaxea* colonies exhibited any environmental damage, such as lesions or bleaching, consistent with the finding that they are more tolerant of sedimentation**.** Studies suggest that coral reefs exposed to a high degree of sedimentation steadily shift towards coral colonies that are sediment-tolerant (McClanahan and Obura, 1996). Therefore, the house reef is anticipated to shift toward less coral diversity in the coming years as sediment-intolerant genera die out.

(a) (b) (c)

Figure 24. Current pictures of the Mnemba House reef. (a) Concave sections of coral colonies are often sediment-filled. (b) Large areas of coral rubble characterize the northern portion of the reef. (c) Much of the reef is covered with a layer of fine silt. (K. Grellman)

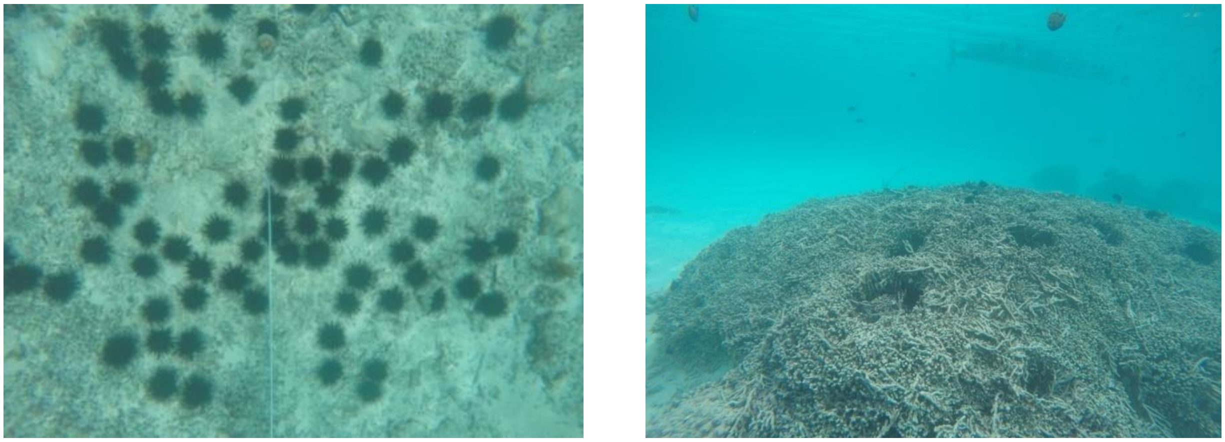
Biological Health Indicators

The heavy sediment deposition also has a direct impact on the fish species at the house reef. It is apparent that the sediment prevents sufficient algal growth that limits overall herbivorous fish. Only five rabbitfish were counted, an unusually low number. There may not be a substantial enough food supply to support a larger population of rabbitfish. Out of the two herbivorous fish species counted, there was a significantly higher abundance of parrotfish, which are better able to survive in the algae-limited environment because they are corallivores and feed on coral as another food source. Therefore, they may be out-competing the rabbitfish.

Although sedimentation is a key factor that causes damage to the house reef, it is important to highlight the other compounding negative factors. Mnemba Island is a marine protected area, but fishing is a regular activity at the surrounding reefs. One Mnemba dive instructor recalled the time she witnessed a large Angelfish (*Pterophyllum)* speared in front of her during a dive (Kooyman, personal communication, 2018). As the human population grows, so does the demand for adequate marine resources, which influences fishermen to turn to destructive fishing practices (Jiddawi and Ohman, 2002). Thus, the lack of indicator fish species' abundance and diversity appears to be the result of the over-exploitation of marine resources. The dominant presence of sea urchins is indicative of top-down fishing, particularly of triggerfish that prey on urchins. Only 11 total triggerfish were surveyed at the reef compared to over 3,000 sea urchins. There is a clear imbalance between the populations, leading to coral degradation from the urchin bloom. The urchins also contribute to reduced algae at the reef (alongside the impactful sediment load), indirectly affecting the herbivorous fish populations. The abundance of coral-degrading urchins is particularly concerning since there is already a low percentage of live coral cover at the reef (3.86%). Young corals may be preyed upon too heavily and frequently by the urchins to reach maturity, which makes regeneration of the reef unlikely if urchin population growth persists.

Only four COTS, the other coral degraders counted in the surveys, were observed during surveys. Although there was a higher number of COTS observed than represented in the surveys, there were far too few COTS to classify their presence as an outbreak. However, their presence is a significant concern since COTS only recently started to appear at the reef (Gibor, personal communication, 2018). Due to their rapid reproduction rate the COTS population should be closely monitored to hinder further coral degradation.

Noticeable damage from tourist traffic was also noted during the study. Although a restricted number of guests are allowed on Mnemba Island itself, many residents and tourists from Unguja Island frequent the house reef by boat. Snorkelers are often seen standing on the coral and kicking up sediment. Unfortunately, they are also encouraged to feed the fish, spurring booms of certain fish species and further ecosystem imbalances. In addition, boat captains are careless about the placement of anchors and often crush or damage coral while mooring.



(a) (b)

Figure 25. Pictures showing anthropogenic pressures on the Mnemba house reef. (a) Transect line #3. (b) Anchor damage to a coral colony. A moored boat can be seen in the background. (K. Grellman)

Erosion Mitigation and Conservation Practices

The data clearly indicate that the reef is imperiled by sedimentation and anthropogenic pressures. As Mnemba Island continues to erode, it is one step closer toward destruction and the coral reef accrues greater sediment. Models show that continued degradation of the easternbordering fringing reef coupled with just 10 centimeters of sea level rise has the potential to increase the wave height by 40% on the eastern shore (Swanepoel, 2016). If immediate action is not taken, the island and all it hosts will be gone in a matter of years. It is clear that the past and current erosion mitigation attempts have not been successful. It is crucial to address their shortcomings and to introduce ways to enhance their effectiveness to save Mnemba Island.

In general, there has been a lack of substantial action taken to mitigate the severe erosion. The Forestry Department has not proposed any significant erosion mitigation plan and has disallowed &Beyond employees from taking any major action themselves. It was conveyed that &Beyond employees are prohibited from removing or moving any of the dead trees that litter the eastern beach and from moving vulnerable infrastructure farther inland on the small island. The Forestry Department prohibits action that might prevent further forest degradation, but the erosion of the island occurs at such a rapid rate that erosion mitigation should be a priority.

The most significant erosion mitigation strategy on Mnemba Island is the sapling project. The sapling project aims to restore island vegetation and thus increase soil stabilization. There are a number of possible explanations for the receding vegetation line: heavy wave action, sea level rise, the direct inundation of salt water, the thinning of the plants by antelope influence, competition from invasive *Casuarina* trees, and a combination of some or all of these factors. The sapling project initiated on the island has the potential to mitigate erosion and fill these vegetation gaps if more energy and resources were put toward the project. Planting began in September of 2017. So far, over 1,000 seedlings have been started in the nursery and 600 plants have been transplanted (Rattray, personal communication, 2018). A complete list of plant species used in the project can be found in Table 8 in the appendix. The Forestry Department, however, has placed limitations on what kind of plants Mnemba Island is allowed to grow. There is no time for such detailed restrictions. Finding the best solution in the shortest amount of time is essential for the island's survival. The sapling project has the potential to mitigate erosion and fill these vegetation gaps if more energy and resources were put toward the project.

(a)

(b)

Figure 26. Images of the sapling project as of April 2018. (a) Sapling starters in the greenhouse. (b) Recently planted *Pandanus* growing in an area of vegetation loss near the eastern shoreline. (K. Grellman)

Mnemba Island closely monitors its suni and Ader's duiker populations to measure their potential impacts on forest vegetation. Five duikers were introduced to the island in 2005 when their population levels reached dangerously low levels. With no predators and an ample food source, their population on Mnemba Island tripled in just 8 years (&Beyond Website). Three suni were brought to Mnemba in 1991, and since then their population has proliferated at such high rates that over 250 individuals have been relocated (Fiske, 2011). Since they are both introduced species on the island, their influence on the forest ecosystem could be significant and negatively impact the sapling project. A number of years ago, an exclusion zone of 10 by 10 meters was fenced off in the forest to measure the extent to which antelopes affected the forest ecosystem. This exclusion zone should be revisited to determine antelopes' influences. If they cause shifts in vegetation, possible habitat alternatives for the antelopes should be discussed.

Mnemba Island has also monitored its green sea turtle nesting population for approximately 10 years (Dunbar, 2011) and is the only protected nesting site for the endangered turtle species on Unguja Island (&Beyond Website). Continued monitoring of the turtle nests is beneficial to the island and the sapling project because unhatched eggs in sea turtle nests are an important nutrient source for beach vegetation (Hannan et al., 2007). Beach integrity improves when sea turtles nest in higher numbers.

As for the reef itself, clear impacts from overfishing can be traced to the lack of marine law enforcement in the Mnemba Island area. MIMCA is the only department that monitors the coral reefs. MIMCA, however, seems to lack any authority and focuses most of its energy on charging tourists a $3 visitor fee rather than patrolling for illegal fishing. Fishermen caught illegally fishing are supposed to be fined, but are instead often just given a warning. There is no documentation or official ticket process for those caught doing illegal activities. MIMCA employees can report illegal activity to the Department of Fisheries, but it is a slow process and often ineffective in taking any real action. Furthermore, the fee collection is intended to go to the Department of Fisheries which then is allocated to the local community, but conversations with &Beyond staff members suggest this rarely happens. Therefore, the lack of fish abundance and diversity is unsurprising. If the reefs are not properly monitored and the laws not strictly enforced, the flora and fauna populations will become further imbalanced and the reef will continue to die.

In an effort to conserve local marine ecosystems, the Ocean's Without Borders initiative was launched in January 2018 on Mnemba Island. In addition to research, Ocean's Without Borders has a strong focus on community engagement and education. Local communities are taught ways to conserve marine resources and are aided in growing vegetables as an alternative food source to lessen their dependence on ocean ecosystems (&Beyond Website). Furthermore, education excursions to the island are run regularly to educate students and community members about the natural environment and conservation practices (Rattray, personal communication, 2018). Involvement with the community is critical for marine conservation. These programs encourage steps to protect the reef. The community is the largest stakeholder in the surrounding coral reefs because their livelihoods rely directly on marine resources. Therefore, continued and expanded educational programs are recommended to raise awareness about the rapid degradation of the reef.

Stakeholders on Mnemba Island have taken some positive steps to protect their rich environment. Due to the rapid rate of erosion and resulting reef degradation, however, grander and more intensive measures must be taken. With heavy coastal erosion, substantial human impacts, lack of effective protection measures, and global threats with local implications, the house reef is fighting an uphill battle for its survival. If this tourist destination and ecological hotspot is to be saved, prompt decisions must be made and enacted.

Conclusion

The importance of coral reefs to the local communities of Zanzibar cannot be stressed enough. Thus, monitoring their health and identifying their primary threats is crucial to their conservation. This holistic health assessment of the Mnemba Island house reef found that it is in critical condition. Although a series of complex processes impact coral reef health, heavy sediment deposit is a primary cause of the destruction. Sediment is getting deposited on the reef at rates beyond the lethal limit of 10 mg cm^{-2} d^{-1} but may vary seasonally. The lack of algal growth indicates the direct effect on photosynthetic activity, which impacts fish species and other animals in the ecosystem. Much of the coral has already died - only 3.86% of the reef benthos is live coral cover while 67.1% is coral rubble and dead coral cover. The reef lacks coral diversity and will become even less diverse as sediment-intolerant corals continue to die out. The thriving sea urchin population is an indication of the additional threats to the reef driven by human activity, and the nearly unrestricted fishing compounded with tourist use places a high level of stress on the reef. Further study of the site is necessary to determine the rate at which the reef is degrading and to monitor the effectiveness of any conservation measures.

The poor condition of the reef indicates that the current conservation practices are not providing sufficient ecological protection to the island and to the reef. The sapling project is an encouraging first step in building up coastal vegetation, but must be intensified to make a significant impact. Additionally, cooperation between the Department of Forestry and Mnemba Island is critical for enforcing an erosion mitigation plan. With the current rate of erosion and lack of action, the island will not be able to support the hotel – or much else – in a matter of a decade or more. Considering the economic revenue generated by tourist activity on Mnemba Island and the innumerable ecological benefits of the island, the government and community should enforce protective measures as a top priority.

Tracing the erosion history of Mnemba Island and linking it to coral reef health provides a unique perspective on the human-environment interface. The erosion was enhanced by human activity and has gone unmitigated for over 20 years. It represents on a small scale the level of severity that global threats are posing to coastal communities. On Mnemba Island, these impacts and further risks can no longer be ignored – both for the sake of the environment and for those people who rely on it. Although the situation is dire, it is not too late. If prompt measures are enacted Mnemba Island can continue to support the rich ecosystem and diverse wildlife that inhabit it.

Recommendations

Immediate action must be taken to mitigate the compounding threats to Mnemba Island and its reefs. It is foremost recommended that the Department of Forestry take a more active role in helping Mnemba Island mitigate the severe erosion. Islands are particularly susceptible to climate change (Kueffer and Kinney, 2017), as evidenced by the current status of Mnemba Island, and should be a priority for the government in terms of ecological protection and conservation. The Department of Forestry should enable experimentation with more plant species to determine which is the most successful for out-competing *Casuarinas*. The sapling project is an effective first step forward in strengthening the shoreline, but Mnemba Island needs more support if it is to be successful. The sapling project should be a priority for the island.

Throughout the researcher's 4-week stay on the island, only one employee was actively working on the project. There should be more employees specifically hired to work in the greenhouse so a higher volume of plants can be planted. It would also be beneficial to have a residential botanist on the island to monitor the plant species and ensure the most effective species are being planted. In addition, once the most successful plant species are determined, larger and more mature plants should be transplanted in an effort to speed the soil stabilization process. It is also recommended to plant more *Ipomoea pescaprae* due to its success in stabilizing the shoreline in coastal areas on Unguja Island that experience similar severe erosion (Mustelin et al., 2009).

Mnemba employees should also be allowed to move the fallen trees on the beach in such a way that they absorb wave energy rather than enhance it. The shoreline would be more protected by simply turning the trees parallel to the shore rather than keeping them perpendicular to the shoreline. This way, they will better trap the sediment that is lifted up in the water column, and prevent further transport to the house reef. In this manner, the beach will be more resilient.

As past attempts show, any hard or soft structures designed for mitigating coastal erosion will be ineffective on Mnemba Island for a number of reasons, the most significant being that there is not enough foundational support for a substantial structure. Tracing the erosion problem back to its initial roots provides insight for the best mitigation strategy: Mnemba Island was protected from enhanced wave activity on the eastern shore by the surrounding fringing reef until it was heavily degraded, most likely by anthropogenic activity. Therefore, it is recommended that an artificial reef be installed to act as a breakwater. Studies show that artificial reefs are an effective method of mitigating coastal erosion (Broughton, 2012; Harris, 2012; Kim and Mun, 2008). There are numerous case studies on artificial reefs that successfully enhance beach accretion such as the Gran Dominicus project, constructed in 1998, and the Iberostar project, constructed in 2002, both in the Dominican Republic. Both of these projects utilized Reef Balls to increase the biodiversity of the reefs and to mitigate wave impact on the shoreline (Harris, 2012). These projects could be used as a model for Mnemba Island. Furthermore, there would be no aesthetic impact from the island's viewpoint, preventing any negative influences on the Lodge experience. In addition to attenuating waves, artificial reefs have the potential to increase marine biodiversity and abundance (Broughton, 2012) and to reduce the heavy diving pressure placed on the other Mnemba reefs (Tynyakov et al., 2017).

As for impacts on diving preferences, a study on divers' responses to artificial reefs in the coastal waters of Eilat showed that the divers enjoyed diving on artificial reefs because it diversified their ocean experiences (Tynyakov et al, 2017). A second study conducted at the same location showed that there was a greater average diver density at the artificial reef than at the surrounding natural atolls (Belhassen et al., 2017). Nevertheless, there are huge potential impacts from artificial reefs that must be taken into account, such as the introduction of invasive species that could dramatically alter the natural ecosystem (Broughton, 2012). Therefore, more research must be done on this particular topic before any major implementation steps are taken.

As for anthropological impacts to the reef, tourists should be given lessons on snorkeling etiquette. It is common for people to unknowingly do things that are harmful to the reef, such as touch the coral or stand on the coral. By giving visitors a brief lesson on the environment, much damage could be avoided. Of course, that is up to the tourist operators who often do not place a priority on conservation. Therefore, when MIMCA collects tourist fees, they could give a brief rundown of what human impacts harm the reef. Feeding the fish should also be prohibited, as it causes population booms of certain species that further offset the ecosystem balance. Nevertheless, the damage to the house reef has reached such an intense level that it is strongly recommended that the number of people allowed per day on the reef be restricted, thereby relieving some of the pressure placed on the reef and the surrounding environments.

In addition, MIMCA must shift their focus. Rather than spend most of their energy collecting tourist fees, they should center their efforts on illegal fishing activities. Interviews with Mnemba Island employees revealed that MIMCA should be given more resources to better enforce the law and carry out their protective responsibilities.

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Appendices

Informal Interviews:

Andy Gibor, *General Manager, Mnemba Island Lodge (2 years)*
Topics Discussed: History of Mnemba Island, island erosion.
Nyambu Juma, *MIMCA Employee (10 months)*
Topics Discussed: MIMCA services, fishing pressures, tourist fees.
Sabine Kooyman, *&Beyond Dive Instructor (2 years)*
Topics Discussed: Reef conditions, fishing pressures, tourist etiquette, MIMCA.
Sufi Makame, *&Beyond Dive Instructor (11 months)*
Topics Discussed: Reef conditions, past conditions of the reef, fishing pressures, tourist etiquette, MIMCA.
Shawn Raaths, *Maintenance Facilities Manager, Mnemba Island Lodge (1 year)*
Topics Discussed: History of Mnemba Island, island erosion, MIMCA, sapling project.
Scott Rattray, *General Manager, Mnemba Island Lodge (2 years)*
Topics Discussed: History of Mnemba Island, island erosion, conservation measures, sapling project, Mnemba Island community service partners.

Additional Tables:

HARD STRUCTURES	SOFT STRUCTURES
Sea Walls ➢ Vertical structures parallel to the shore. ➢ Used as a last resort to block waves from coastal structures.	**Beach Nourishment** ➢ Placement of sand on beaches to increase their width. ➢ High potential for introduction of invasive species.
Revetments ➢ Sloping structures made out of piled rocks, wood, or coconut shells. ➢ Sometimes considered *soft structures*if constructed out of natural materials.	**Re-vegetation** ➢ Planting of indigenous beach vegetation to stabilize the sand (Mustelin et al., 2009).
Submerged Breakwaters ➢ Offshore structures running parallel to the shore, structure crest height is below the water level. ➢ Absorb wave energy before reaching the shore.	**Beach Dewatering** ➢ Removal of water from the beach to increase the natural accretion process. ➢ Ecological impacts generally unknown.
Emergent Breakwaters ➢ Offshore structures running parallel to the shore, structure crest height is above the water level. ➢ Hold sand inland by reducing wave impact.	**Geotextiles** ➢ Bags filled with sand or another similar material and piled along the shoreline (Swanepoel, 2016).
Artificial Reefs ➢ Same function as a submerged breakwater. ➢ Mimic characteristics of a coral reef. ➢ Can attenuate up to 60% of wave energy.	
Groins ➢ Extend perpendicularly from the shoreline into the sea. ➢ Trap sand as it is transported along the beach.	

Table 7. Summary of various hard and soft engineering structures for mitigating coastal erosion (Thornton et al., 2012).

BEACH PLANT SPECIES		
Common Plant Name	**Swahili Name**	**Scientific Name**
Scaevola	Mtumbaku	*Scaevola*
Beach Morning Glory	Mlakasa	*Ipomoea pescaprae*
N/A	Mdaranba	*Pemphis*
N/A	N/A	*Launaea*
FOREST PLANT SPECIES		
Dune Myrtle	Mkaaga	*Eugenia capensis*
Coast Milkwood	MvuruVuru	*Sideroxylon*
White Milkwood	MtundaNgombe	*Sideroxyloninerme*
OTHER PLANT SPECIES TO TEST		
N/A	Mkolempwa	*Grewia mollis*
Common Fig	Mlimbo	*Ficus carica*
N/A	Mkadi	*Pandanus kirkii*

Table 8. Sapling project plant species. Table adapted from Programme for Mnemba Rehabilitation and Nursery Establishment, 2016.

Sample Raw Data:

Common Name	Scientific Name	Number of Individuals
Stareye Parrotfish	*Calotomus carolinus*	11
Bridled Parrotfish	*Scarus frenatus*	2
Swarthy Parrotfish	*Scarus niger*	1
Redlip Parrotfish	*Scarus rubroviolaceus*	11
Bullethead Parrotfish	*Scarus sordidus*	71
		Total: 96
African WhitespottedRabbitfish	*Siganus sutor*	5
		Total: 5
Clown Triggerfish	*Balistoides conspicillum*	1
Orangestriped Triggerfish	*Balistapus undulatus*	3
Black Triggerfish	*Melichthys niger*	3
Pinktail Triggerfish	*Melichthys vidua*	1
Halfmoon Triggerfish	*Sufflamen chrysopterus*	3
		Total: 11

Table 9. Total abundance of each fish species.

Station Number	Trap	Dry Sediment Weight (g)	Average Dry Sediment Weight per Station (g)
1	A	2.0	
	B	0.5	1.25
2	A*	3.5	
	B	22.5	13.0
3	A	2.0	
	B	3.5	2.75
4	A	19.5	
	B	12.5	16.0
5	A*	15.0	15.0

Table 10. Dry weight of collected sediment in sediment traps. *Indicates which traps were found horizontal 7 days after deployment.

Calculations:

Fish Diversity Indices

$$\text{Shannon} - \text{Wiener Diversity Index (H)} = -\sum_{i=1}^{s} pi \ln pi$$

$$\text{Simpson Diversity Index (D)} = \frac{1}{\sum_{i=1}^{s} p_i^2}$$

Sample Calculation for Parrotfish Diversity:

s (number of species) = 5
N (total number of individuals) = 96

Species	n	n/N	p_i	p_i^2	$\ln p_i$	$p_i \ln p_i$
	71	71/96	.7396	.5470	- 0.3016	- .2231
	11	11/96	.1146	.0131	- 2.166	- .2482
	11	11/96	.1146	.0131	- 2.166	- .2482
	2	2/96	.0208	.0004	- 3.873	- .0806
	1	1/96	.0104	.0001	- 4.566	- .0475
Sum				0.5737		- .8476

Table 11. Calculated values of parrotfish species to determine its diversity indices.

$$\text{D} = \frac{1}{0.5737} = 1.743$$

$$\text{H} = -(-.8476) = .8476$$

Sediment Flux

$$F = \frac{\mathrm{W}}{\mathrm{A_{st}\ x\ T}}$$

Where

F = Sediment flux rate (mg cm^{-2} d^{-1})
W = Sediment weight (mg)
A_{st} = cross-sectional area of sediment trap (cm^2) = 95.03 cm^2
T = time of trap deployment (d) = 18 days

Sample calculation for Trap 1A:

$$F = \frac{\mathrm{2000\ mg}}{\mathrm{95.03cm^2\ x\ 18\ d}} = 1.17\ \mathrm{mg\ cm^{-2} d^{-1}}$$