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Vulnerability and Adaptability of Mangrove Forests on Misali Island, Zanzibar, Tanzania

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SIT Study Abroad

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Zanzibar Coastal Ecology and Natural Resource Management Fall 2019
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Acknowledgements

I would first like to thank the three rangers of Misali Island; Mohammed, Haji, and Said, who cooked for us, cared for us, and helped us with Swahili throughout our stay. I would especially like to thank Mohammed for sharing his extensive knowledge about mangroves and taking me for two-hour walks around the island to show me hidden mangrove forests. I would like to thank Abby and Raegan for being superb camp buddies, snorkeling partners, and Bananagrams opponents. Thank you to spring tide for being sand-fly free and not almost-flooding our tent. I would also like to thank the rest of the SIT gang for making this entire experience boatloads of fun and being lifelong friends. Lastly, I would like to thank Said Omar and Richard Walz for all their hard work behind the scenes to make this experience possible. Their genuine care for each and every one of us made this a special experience and an incredible four months.

Abstract

As climate change threatens to cause heightened sea levels and decreased rainfall patterns in the Indian Ocean, mangrove forests are forced to adapt or suffer. This study aims to analyze the persistence of four prominent mangrove forests on Misali Island based on vulnerability and adaptability. The study focuses on three types of forests: overwash, coastal fringing, and scrub. Forest A, an overwash forest, was the main site of study and was surveyed for species type and seedling/sapling counts using ten transects which ranged from 40 to 91.7 meters in length. Data was analyzed in order to determine biodiversity, zonation, and reproductive success of the forest as a whole. Each factor was ranked on a scale of vulnerability to adaptability based on corresponding numerical values. Results showed the presence of seven species in Forest A with a high biodiversity. The forest was split into four zones which displayed strong zonation, as certain species prefer more inundated niches while others prefer drier niches. Overwash forests were found to be more adaptable than both coastal fringing and scrub forests and will likely persist the longest on Misali Island.

Dhahania

Wakati hali ya tabia nchi ikisababisha madhara na kusababisha bahari kupanda juu na upungufu wa mzunguko wa mvua katika ukanda bahari ya hindi, msitu wa mikoko ulijilazimisha kuhimili mabadiliko ya hali ya tabia nchi au kuathirika . Utafiti huu ulikuwa na madhumuni ya kuchambua uhimilivu wa mikoko katika kisiwa cha Misali kulingana na mazingira magumu na uhimilivu . utafiti huu ulifanyika katika maeneo manne ya misitu ya koko , ikiwemo mitu ilijitenga, mikoko ya maweni. Msitu A, msitu ulio jitenga , hili ni eneo kuu la utafiti na lilipimwa kwa ajili ya aina za mikoko kwa ajili ya miche michanga /miche midogo sana kwa kutumia transekti 4 pamoja na kuhesabu kuanzia mita 40 mpaka mita 91.7 kwa urefu uchambuzi wa taarifa ulifanywa kwa ajili ya kuchambua aina za mikoko, maeneo, na uzazi wa mikoko kwa ujumla. kila kipengele kilirekodiwa katika hali mazingira magumu na uhimilivu kwa kulinganisha idadi zake . matokeo yanaonesha kuna aina saba za mikoko katika msitu A pamoja na aina nyingi za mikoko . msitu uligaiwa katika maeneo 4 yanayoonekana ni imara , baadhi ya aina zinapenda zaidi kuota katika eneo maalum mingine inaota katika maeneo makavu , mikoko iliojitenga inaonekana kuwa na uhimivu zaidi kuliko mikoko ya mwambao ambayo itadumu kwa muda mrefu katika kisiwa cha misali.

Introduction

Mangrove forests are among the most valuable ecosystems in the world. With the impending climate change, sea level is expected to rise between 0.2 and 1.0 meters over the next century in Zanzibar (Tech. Report, 2012) and rainfall patterns show a steady decline throughout Africa (Othman, 2019). The response of mangrove forests globally is largely unknown. Mangrove forests are impacted by both climatic and anthropogenic factors, making them vulnerable. Changes in sea level, salinity, rainfall patterns, and storm intensity as a result of climate change pose the greatest threat to coastal mangrove forests, ending with adaptation or mortality. While scientists agree that the increase in temperature will make mangrove forests more productive, they disagree whether sea level rise will pose significant risks to mangrove forests and call for strategic management for their protection (Ellison, 2015) and/or simply force mangroves to adapt (Lovelock & Ellison, 2007). This question of survival ultimately depends on the ability of mangroves to adapt to the changing climate. Three factors will contribute either to the vulnerability or the adaptability of mangrove forests: biodiversity, zonation, and reproductive success. The purpose of this study is to determine whether mangrove forests on Misali Island will persist in the future during impending and significant climatic changes. This will be determined by the use of a scale relating vulnerabilities to adaptabilities which ranks mangrove forests in their degree of biodiversity, zonation, and reproductive success.

This study is significant because it investigates how equipped coastal mangrove forests are to adapt to future changes in climate. These findings are crucial in developing a management plan for Misali Island and determining if more drastic measures are necessary in the future of Misali's conservation. This study also provides a baseline to determine which species of mangroves and types of mangrove forests are most and least vulnerable. The findings from

Misali's mangrove forests may be translated to other small-island mangrove forests to determine which forests globally are at the greatest risk and which are not threatened given their respective adaptations and vulnerabilities. With this information, measures can be taken to anticipate and mitigate the future damage to mangrove forests.

Background

The following sections will provide several key concepts essential to the comprehension of this study as well as the location and context of the study site.

Key Concepts

Mangrove forests are coastal and halophytic, which means they thrive in salt water-dominated ecosystems. They occupy tropical settings where the temperature remains above 20°C year-round and fluctuates no more than 5°C (Kathiresan, 2004). Mangroves grow vertically through a process called accretion, which is the gradual accumulation of additional layers (Krauss, 2014). Mangroves have significant importance in coastal ecosystems for flora, fauna, and human communities given the unique habitat they provide. Firstly, they offer storm protection by buffering the coast from wind and wave action. Mangrove roots trap sediments and slow water velocity to increase sedimentation, preventing wave action and tides from causing coastal erosion. Mangroves also prevent sediments from reaching the ocean, where they can damage and suffocate coral reefs and sea grass beds. Mangrove forests act as carbon sinks on a global scale. Their substrates store more carbon than most terrestrial soils and salt marsh soils, making them a vital component in the global carbon budget (Lovelock & Ellison, 2007). They are also crucial habitats for fish nurseries, given that they offer protection while still maintaining close proximity to coral reef and seagrass habitats (Waycott). Many human communities rely on the strength of mangrove wood for building furniture, boats, and architecture. Humans also utilize the fruits and seeds of mangroves for medicinal purposes (Othman, 2109). Mangroves vary considerably among species in root structure (Dahdouh-Guebas et al., 2007), tolerance of salinity, and preferred substrate. These factors are responsible for the location and distribution of mangrove species on a global scale as well as within a single forest.

There are three mangrove forest types found on Misali Island that are observed in this study: overwash, coastal fringing, and scrub. Overwash forests are small mangrove islands located in the intertidal zone and inundated during every tidal cycle. They are typically separated from the shoreline and disconnected from any terrestrial mangrove forest. Coastal fringing forests are similar to overwash forests in that they are inundated during every tidal cycle; however, they are located more inland and typically have a terrestrial component to them. With only one side exposed to wind and wave action, coastal fringing forests are more protected than overwash forests. Scrub forests are low-lying terrestrial forests which form along the coast but are never inundated during the tidal cycle (Kathiresan, 2004). These three types of mangroves forests have different vulnerabilities and adaptabilities given the various circumstances in which they exist.

Vulnerability and adaptability are two concepts at the foundation of this study. *Vulnerability* can be defined by three factors: exposure to stresses, associated sensitivities, and adaptability (Ellison, 2015). In this study, the factors exposure to stress and associated sensitivities will be considered on a scale facing adaptability. *Adaptability* is defined as the ability to change in order to meet the needs of a new situation. Mangroves vary in adaptability largely based on species type, which determines root structure, tree strength, and inundation and salinity preferences. The three measurements of vulnerability and adaptability at the focus of this study are biodiversity, zonation, and reproductive success.

The first contributor is *biodiversity*, or the variety of species present in a location. Macintosh & Ashton (2002) define biodiversity of existing at three levels in a forest: genetic, species, and ecosystem. The focus of this study will be biodiversity on a species level, given that the aim is to consider the success of mangroves as an independent event and to assume that any influence by other organisms is insignificant. Not only does biodiversity account for the number of species in an ecosystem, but the relative abundance of the species present. A mangrove forest with high biodiversity will have more species evenness rather than a forest with low biodiversity. Biodiversity in mangroves is an important measure of resiliency to climate change, given that a certain species may be better equipped to handle a climatic change than others, and therefore more species present would give the overall forest a greater chance of surviving any change. A high biodiversity measure suggests greater adaptability potential than a low biodiversity measure.

Zonation is a second factor that could suggest vulnerability or adaptability. *Zonation* in forests is the ordering of species at a given location based on elevation or substrate gradient. In mangrove forests, zonation is most frequently observed as certain species clustering in different areas of the intertidal zone depending on preferred inundation and/or salinity (Ellison et al., 2000). Zonation is a measure of adaptability given that mangrove forests with higher zonation should be better suited to handle a changing climate. In a mangrove forest with high zonation, various mangroves species find success in different niches given their specific adaptations. For example, the tallest and strongest species may be found on the coast as they are best suited to handle strong winds and wave action. They provide protection for species further inland, which are less suited for wind action but more adapted to other conditions. In this way, zoned forests have the highest adaptability by having the capability both to collaborate in their roles and to adapt to a particular niche. The higher the zonation, the greater the chance of a species in the forest adapting to climate change, such as higher inundation levels or increased salinity.

Reproductive success is the last factor measured on the scale of vulnerability to adaptability and is defined as the ability of a species to produce fertile offspring. A species that has a high seedling to adult ratio is reproductively successful given that a small number of adult trees has yielded a high amount of successful seeds. Likewise, a mangrove species with a high number of adult trees but few young is more vulnerable, as its reproductive success rate is low. Reproductive success will be vital to the overall success of a species given that a species with a high reproductive rate is better equipped to handle changes in the ecosystem brought by climate change.

Study Site

Figure 1. A map of Misali Island showing Forest A (red), Forest B (purple), Forest C (yellow) and Forest D (white)

The study sites for this data collection were the mangrove forests on Misali Island, a coralline island 9 km off the west coast of Pemba Island. Pemba Island is located in the Zanzibar Archipelago in the western Indian Ocean. Pemba and Zanzibar islands lie off the eastern coast of Tanzania in East Africa. Data was collected primarily on a forest located on the northeastern corner of the island. Misali Island is approximately 1.5 km from its most northern point to its most southern. The island is government-owned and partially protected. While there are no permanent residents of the island, two out of three rangers reside on it at any given time. There are two temporary camps located on the island, one on the east side and one in the north, in which fishermen live temporarily, usually for no more than two weeks at a time. Tourists are able to visit the island during the day by boat, but there are no amenities or facilities located on the island and no overnight stays permitted. As the main visitors to the island are fisherman, conservation measures have been taken in order to protect Misali's diverse marine life. Misali is divided into extractive and non-extractive zones in order to reduce overfishing. Fishing and collecting invertebrates is prohibited in non-extractive zones and permitted in extractive zones.

The primary forest in which data was collected, named Forest A for the purpose of this study, is an overwash mangrove forest completely inundated at high tide and dry at low tide. It is the second largest mangrove forest and the largest overwash mangrove forest on Misali Island (Benson, 2018). The forest has a length along the beach of 200 m and a varying width averaging about 62 m, giving Forest A a total approximate area of 12,400 m^2. This forest was selected for survey given its proximity to the open ocean, which causes high vulnerability and a potential for zonation, as well as easy accessibility. Three additional mangrove forests, named Forest B, Forest C, and Forest D, were also studied but not formally surveyed. Forest B is a composed of a scrub forest and a small overwash forest located on and around West Island. This island is a small coral rag island located approximately 200 m off the west coast of Misali Island. The scrub forest, atop West Island, is a combination of mangroves and other vegetation. Forest C is also located on the western side of Misali Island and is a coastal fringing forest. This forest is accessible through a small stream running from the ocean into the forest, which allows for inundation during the tidal cycle. Forest D lies directly behind Tiwani Beach and is located at a pond in which the water level is driven by the tides. This forest identifies most closely with a coastal fringing forest, though it is not located directly on a coastline.

Of the ten mangrove species present in the Zanzibar Archipelago, nine are located on Misali Island: *Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal, Heritiera littoralis, Pemphis acidula, Rhizophora mucronata, Sonneratia alba, Xylocarpus moluccensis* and *Xylocarpus granatum*. While Misali is home to overwash, coastal fringing, and scrub forests, the focus of this study is an overwash forest, as this forest type will be the most affected by rising sea levels given its consistent inundation. Scrub and coastal fringing forests will also be observed for comparative species composition.

Methods

Data was collected in a three-week timeframe, beginning on November 7th and ending on November 28th. The methods of this study include both field work methods and data analytics. A vulnerability to adaptability scale with five rankings on which reproduction, biodiversity, and zonation can be placed was developed. In order to do so, five rankings were assigned to specific numerical ranges in the unit in which each factor is measured.

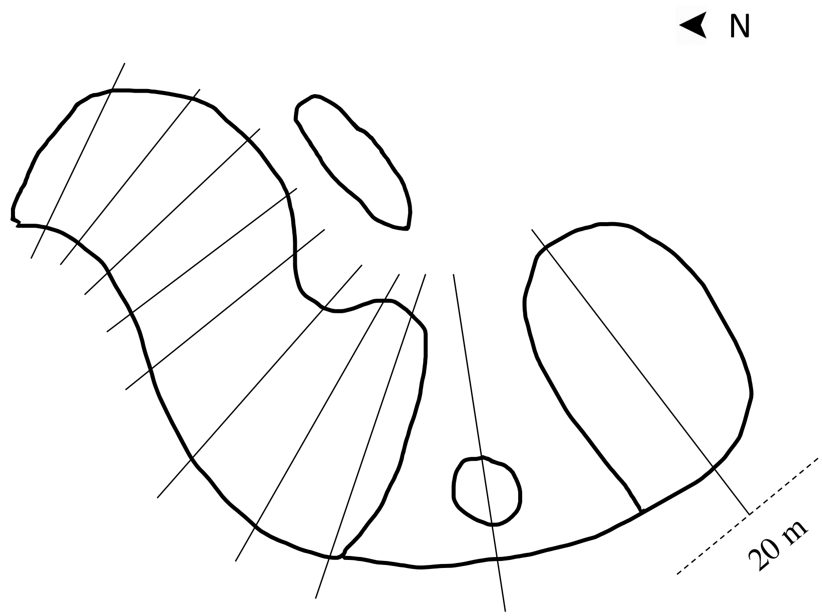

Figure 2. Layout of transects in Forest A (not depicted exactly to scale)

Before laying transects, I spent three days assessing the mangrove forests on Misali Island and observing the tidal cycle. I first measured the length of Forest A with a 50 m tape to establish how many transects in total would be laid. There were 10 transects in total in Forest A, with a 0-5 m gap between each transect, and measured with a 50 m measuring tape. Given that the shape of the forest and shoreline were slightly curved, transects were not necessarily parallel to one another, but ran perpendicular to the beachline (Figure 2). A compass was used to ensure the linearity of each transect. Transects were laid 1-2 hours before low tide. Each transect ran the width of the forest, approximately west to east, running from the last mangrove tree (0 m) toward the beach. This was done in order to maximize time where the forest was not inundated after low tide. Each transect range was 20 m in width (10 m on each side of the transect line) and varied in length depending on the width of the forest at the particular location. For each transect, I began at the 0 m point and walked landward surveying a series of factors. Every mangrove tree within the transect range was noted for its length along the transect, approximate distance from transect (right or left), and species type. Also noted was the presence and number of seedlings and saplings. For each seedling and sapling, the species type and distance along the transect was recorded. Each transect was also drawn immediately following data collection in order to account for the presence of any boulders, bare patches, or other possible influences on forest composition. Furthermore, dominant substrate type was also recorded.

In order to document general forest composition, five additional transects were laid 40 m apart, mimicking the positions of Transects 1, 3, 5, 7, 8, and 10. Each transect was about 20 m in length, running from 20 m into the forest towards the beach. For each of these transects, species type and diameter at breast height (DBH) were recorded for trees within 5 m of each side of the transect.

Forests B, C, and D were also studied in order to compare overwash mangrove forests with potentially different species composition. The entirety of Forest B was able to be observed due to easy accessibility. I made an estimate of adult mangroves as well as the number of seedlings and saplings present. Due to accessibility issues, Forest C was observed from the beach only and a narrow passageway created by a stream which ran through the middle of the forest. Seedling and sapling numbers were estimated for the small section observed as well as the count of mature species; however, no estimations for the entire forest were made given the unpredictability and large size of the unvisited forest area. Forest D was also studied from a vantage point given limited accessibility. I recorded species types, seedling and sapling counts, and made the relevant estimations for the total forest. In addition to the study of Forests A, B, C, and D, I walked around the coastal perimeter and around the interior forest of Misali Island multiple times in order to document all mangroves species present on the island both within and outside of noted forests. I recorded the location of adult trees, seedlings and saplings, and seedpods.

After collection, data was analyzed in Microsoft Excel 2012 in order to compare biodiversity, zonation, and reproduction on a like scale. In order to qualify data for each category, a ranking system for each of the three factors was created. Each factor was assigned five rankings that correlate to specific units of measure. This was done in order to establish a quantitative, universal correlation between the rankings, one through five, and the numerical values of measurement for each factor.

Biodiversity was measured using the Simpson's Diversity Index because this index takes into account not only diversity in tree species but relative abundance among species. Simpson's Biodiversity indexes from 0.00 to 0.20 were ranked one, 0.21 to 0.40 were ranked two, 0.41 to 0.60 were ranked three, 0.61 to 0.80 were ranked four, and 0.81 to 1.00 were ranked five. For the reproductive success calculations, the ratio of young trees, including both seedlings and saplings, to mature trees was divided into five categories. The number of young trees were divided by the number of mature trees to get a numerical value able to be ranked. A number less than 1 correlated with a ranking of one. Numbers 1-5 were ranked two, 6-10 were ranked three, 11-15 were ranked four, and numbers greater than 15 were ranked five. Zonation was ranked using concepts established in Ellison et al. (2000). The forest was divided into four zones based on groupings in species composition apparent in the transect surveys. Biodiversity measurements were calculated for each of the four zones using the Simpson's Diversity index and then averaged for each zone in order to establish the level of zonation in the forest as a whole. This number was then ranked; a lower index suggested higher zonation. Biodiversity averages from 0.00 to 0.20 were ranked five, 0.21 to 0.40 were ranked four, 0.41 to 0.60 were ranked three, 0.61 to 0.80 were ranked two, and 0.81 to 1.00 were ranked one. Once the rankings for each factor were established, the entire forest was ranked in biodiversity, zonation, and reproduction. Each factor was placed on the vulnerability to adaptability scale in order to determine the adaptability or vulnerability of the forest as a whole.

Results

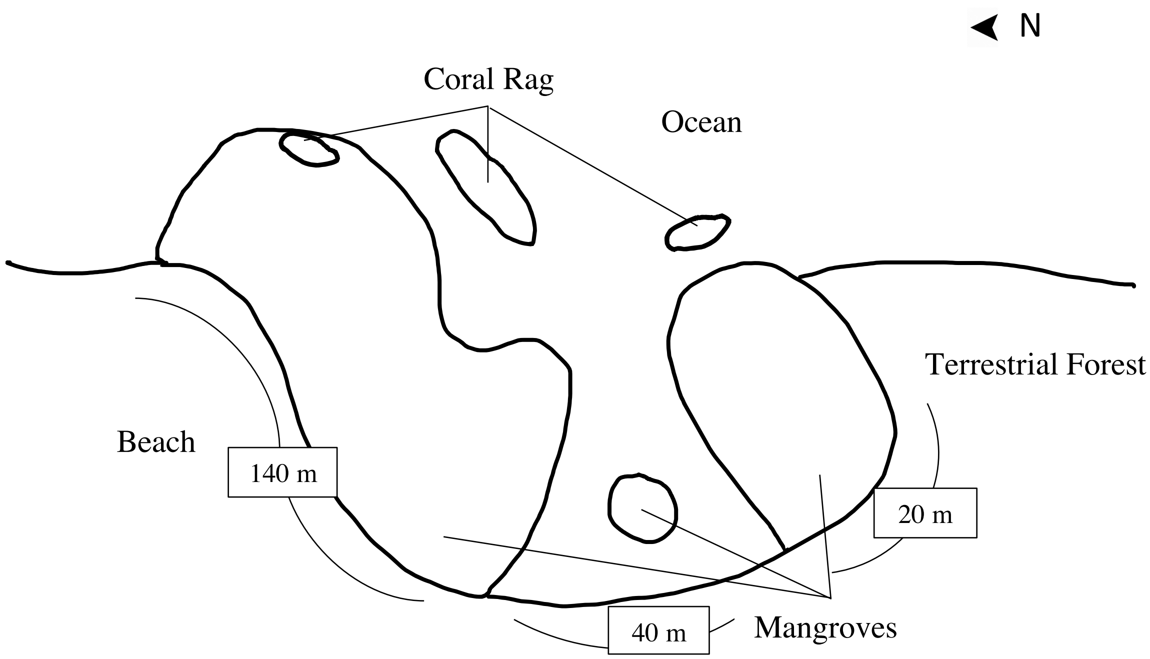

Figure 3. The composition of Forest A and shoreline measurements

Six species of mature trees were recorded in Forest A: *Bruguiera gymnorrhiza*, *Sonneratia alba*, *Rhizophora mucronata, Pemphis acidula, Xylocarpus moluccensis,* and *Avicennia marina*. *Ceriops tagal* was also present, but only in seedling form. *A. marina, R. mucronata,* and *S. alba* comprised 97% of the forest, while *P. acidula, X. moluccensis,* and *B. gymnorrhiza* composed the remaining 3%. In Forest A, *A. marina* displayed the largest average DBH (avg = 24.0 cm), and *R. mucronata* displayed the smallest (avg = 12.4 cm). *S. alba* in the forest averaged a DBH of 17.1 cm. The forest was found to be approximately 200 m in length, following the shore line. The largest portion of the forest was 140 m long, in which the substrate gradually changed from predominantly sand to predominantly mud. After 140m, there lay a 40 m gap comprised of mud and two tree patches. The last 20 m of forest bordered terrestrial vegetation and had a somewhat rocky substrate (Figure 3).

Transects varied in substrate composition, water inundation, protection by land masses and trees, and density. Substrate gradually changed from sand-dominated to mud-dominated throughout the transects, with Transect 1 being 90% sand and 10% mud and Transect 9 being 90% mud and 10% sand. Transect 10 was about 50% sand, 30% mud, and 30% rock. While the entire forest was inundated at high tide and dry at low tide, water inundation levels varied among transects based on proximity to the seaward fringe bordering the open ocean and length of time inundated with each tidal cycle. Earlier transects had much greater inundation at high tide with around 2 m of water coverage, while later transects had no more than 1 m at any point in the cycle. Transects also varied in amount of exposure to wind action and high energy sea processes as some had protection from coral rag boulders, terrestrial forests, and other trees (Figure 3). In Transect 2, the first 10 m was occupied by a large coral rag mound. Transects 1 and 3 were the most exposed to the ocean and Transects 4, 5 and 6 were protected by an external coral rag boulder about 20 m from the seaward fringe. Lastly, Transect 10 was protected by both the terrestrial forest to the south and a coral rag island just off the eastern edge of Forest A.

The following results regarding biodiversity, zonation, and reproduction were calculated based solely on the survey performed in Forest A.

Biodiversity

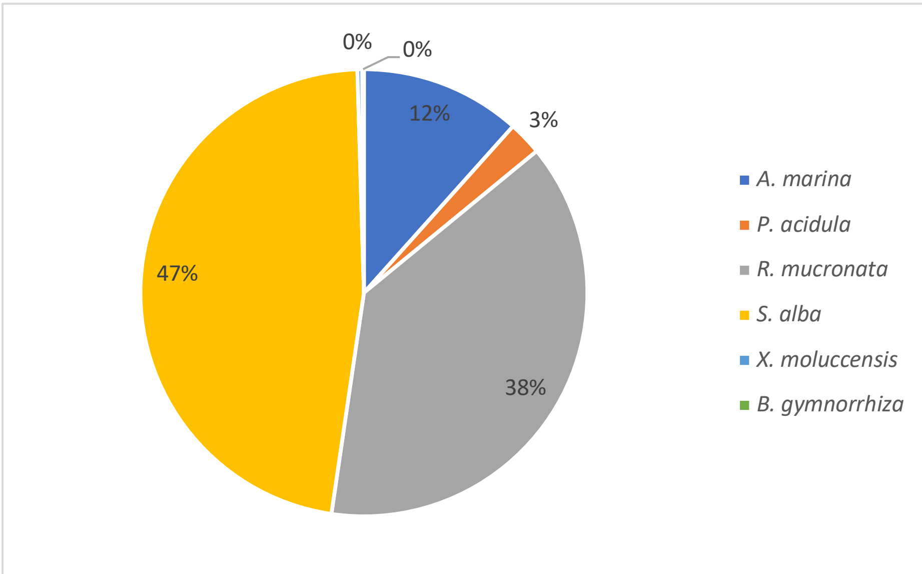

Figure 4. Mangrove composition of Forest A by species

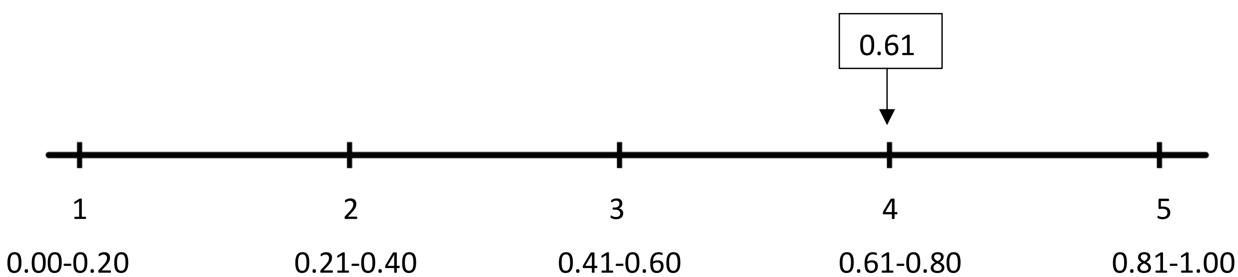

Figure 5. Ranking scale for biodiversity in Forest A measured with the Simpson's Biodiversity Index

S. alba and *R. mucronata* comprised the largest percentage of the forest, with 406 *S. alba* trees making up 47% and 329 *R. mucronata* trees making up 38%. *A. marina* was slightly less frequent, with 100 trees comprising 12% of the forest. Only one *B. gymnorrhiza* tree and three *X. moluccensis* trees were present, together making up less than 1% of the forest (Figure 4). *P. acidula* was only found in Transect 2 atop a coral rag boulder and had 21 trees that made up 3%

of the forest. Forest A scored an overall Simpson's Diversity Index of 0.61, including all six species. This scored a ranking of four on the vulnerability to adaptability scale using the ranking system outlined in the project methodology (Figure 5).

Zonation

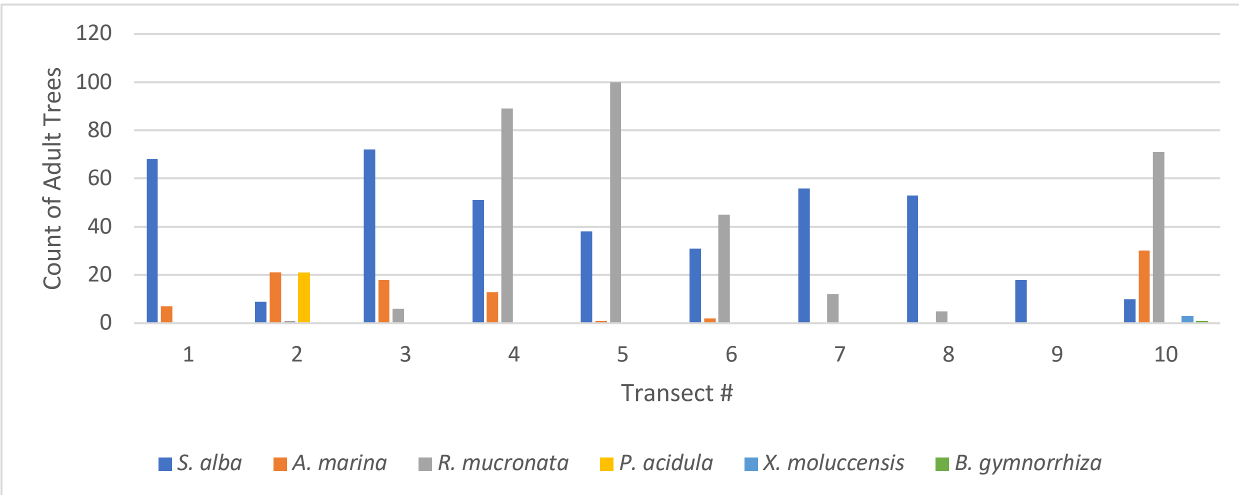

Figure 6. Species composition by transect

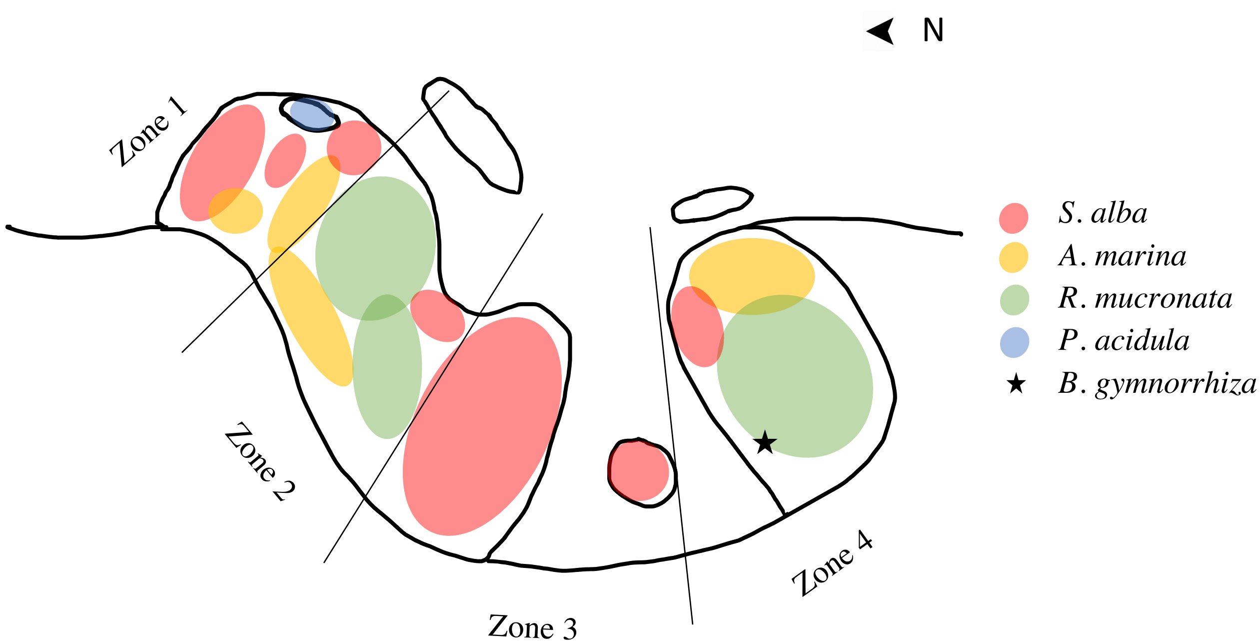

Figure 7. Species composition of Forest A. Species were recorded if numerous were in an area while single trees were not displayed.

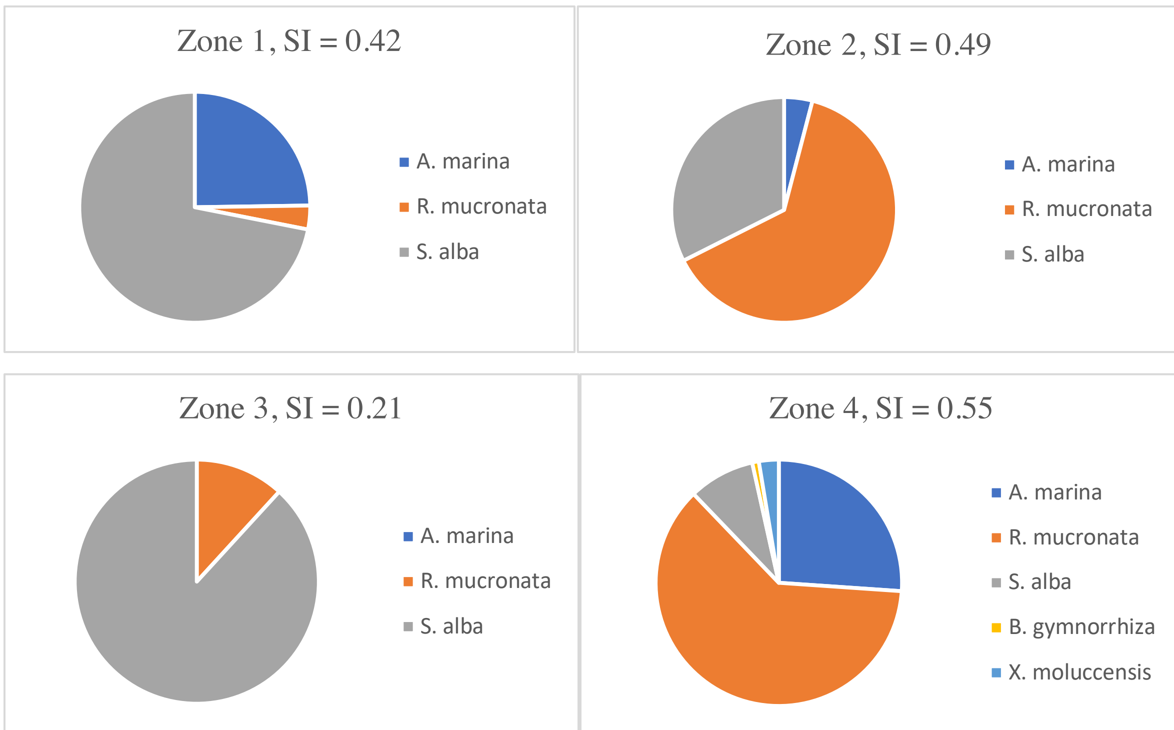

Figure 8. Species composition of zones in Forest A and Simpson's Diversity Index

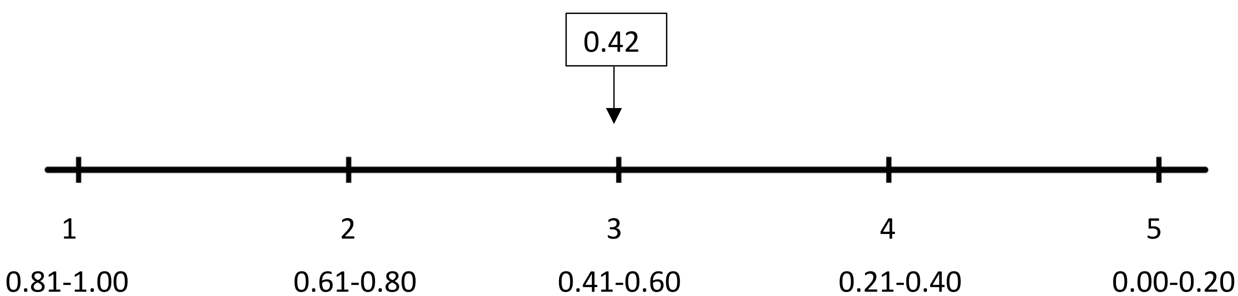

Figure 9. Ranking scale for zonation based on Simpson's Biodiversity Index

Data collected from the ten transects showed collections of dominant species which were grouped into four zones. Transects 1-3 (0 – 60 m) were labeled Zone 1, 4-6 (60 – 120 m) labeled Zone 2, 7-9 (120 – 180 m) labeled Zone 3, and 10 (180 – 200 m) labeled Zone 4. Zones 1 and 3 were heavily dominated by *S. alba* while Zones 2 and 4 are dominated by *R. mucronata* (Figure

6). Zone 4 was the highest in biodiversity, given that both *B. gymnorrhiza* and *X. moluccensis* were found in this zone and no other. *P. acidula* was left out of the zonation calculations given that it was only present in the forest on a 10 m tall coral rag boulder that is never inundated by the tidal cycle. This causes the *P. acidula* present in Forest A to experience different conditions than the rest of the forest and thus was not included in the overall zonation, which was primarily based on water inundation.

In regard to zonation, Forest A ranked 3 on the vulnerability to adaptability scale with the average biodiversity of the four zones being 0.42 (Figure 9). Zone 3 had the lowest Simpson's Index of 0.21 while Zone 4 had the highest of 0.55. Zones 1 and 2 fell in between with indices of 0.42 and 0.49 (Figure 8).

Reproduction

Species	Adult Count	Seedling Count	Sapling Count	Seedlings & Saplings / Adults
A. marina	100	7	0	0.07
R. mucronata	329	1862	85	5.92
S. alba	406	0	6	0.01
C. tagal	0	32	0	32.00*
B. gymnorrhiza	1	17	0	17.00
X. moluccensis	3	0	0	0.00
P. acidula	21	0	0	0.00

Table 1. Reproductive success rates in Forest A
**C. tagal* was said to have one adult tree, rather than zero, for the purpose of getting a real number for the ratio of young trees to adult trees.

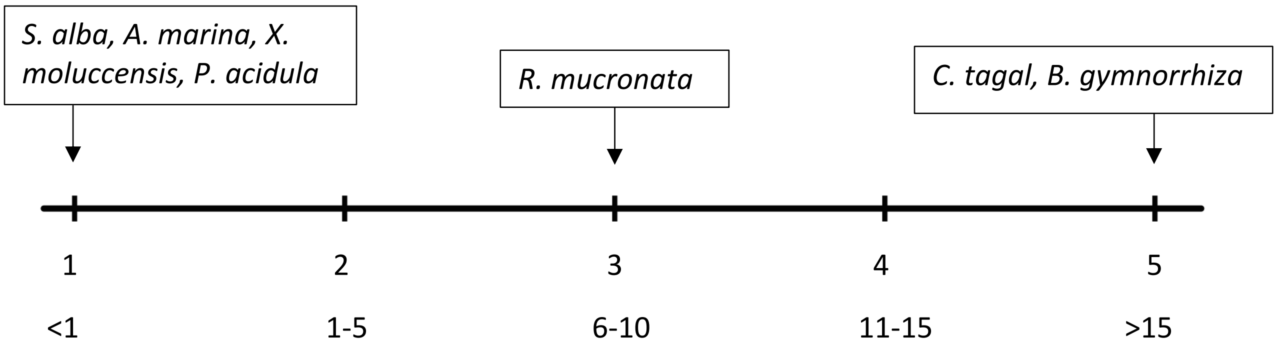

Figure 10. Ranking scale for reproduction based on the ratio of young trees to adult trees

R. mucronata was found to have the highest seedling and sapling count, with 1862 seedlings present in Forest A (Table 1). This was nearly 60 times higher than the next highest occurring species, which was *C. tagal* with 32 seedlings. *C. tagal* ranked highest on the vulnerability to adaptability scale with a score of 32 and a ranking of five, while *X. moluccensis* and *P. acidula* ranked lowest with a score of 0 and a corresponding ranking of one, given that they had no seedlings or saplings present in Forest A. *A. marina* and *S. alba* also ranked a one on the scale, given their low ratios of young trees to adult trees (*A. marina* = 0.07, *S. alba* = 0.01). *R. mucronata* fell between the two with a score of 5.92 and a ranking of five (Figure 10) (Table 1).

The potentially problematic nature of this scoring system is discussed further in the Discussion section of this paper. It explains why it may be unfair to consider *C. tagal* the most successful species in Forest A and *A. marina* the least successful given their various reproductive cycles and success past the seedling stage.

Forests B, C, and D

Forest	A	B	C	D
Species Found	*S. alba* *R. mucronata* *A. marina* *P. acidula* *X. moluccensis* *B. gymnorrhiza*	*R. mucronata* *S. alba* *P. acidula* *B. gymnorrhiza* *C. tagal*	*C. tagal* *R. mucronata* *B. gymnorrhiza* *P. acidula*	*C. tagal* *A. marina*

Table 2. A comparison of mature species found in the four study sites in order of greatest occurrence to least occurrence

Discussion

Results from Forest A show high biodiversity, observable zonation, and various rates of reproductive success depending on species. Observations in Forests B, C, and D as well as isolated mangroves around Misali Island supported these conclusions.

Biodiversity

Tanzania has the highest mangrove biodiversity out of all African countries with ten species in total, closely followed by Mozambique, Madagascar, and Kenya with nine species present (Kathiresan & Rajendran, 2004). Misali Island, home to all ten species found in Tanzania except *Lumnitzera racemosa*, is higher in mangrove biodiversity than most countries. While Misali has most of the predominant species found in East Africa, it also has the rare species *Xylocarpus moluccensis*. The presence of this species raises Misali's conservation value and makes it home to a unique ecosystem. Being located across the Pemba Channel, seedpods coming from Pemba wash up onto Misali's shores driven by currents. This likely explains the island's high biodiversity and number of species present. About 100 seedpods of *Heritiera* *littoralis* were observed at the tide mark on the beach over the three-week time period, and six seedlings occupying the upper beach on the east side of the island. *H. littoralis* prefers to occupy the most landward zone, as found by Fujimoto & Miyagi (1993). If the seedpods of *H. littoralis* were able to move farther inland on Misali Island, they may be able to succeed past the seedling stage and heighten Misali's biodiversity even further.

The high biodiversity resulting in a ranking of four on the vulnerability to adaptability scale (Figure 5) causes Forest A to be well suited to adapt to climatic changes. As climate change brings sea level rise, the forest as a whole may adapt by gradual migration landward. Ellison and Zouh (2012) studied an overwash mangrove forest in Cameroon and found significant seaward edge retreat from 1975-2007 as a result of rising sea levels. By retreating landward, each species maintains its individual niche by migrating as the inundation level grows. Biodiversity is important in this process as more species present in the forest will allow more niches to be filled in new ecosystems and forests with slightly different conditions caused by climate change. If one species is unable to adapt and dies off, the mangrove forest will not suffer detrimentally due to the diversity of the remaining species present.

One notable trend in the biodiversity data was that the Simpson's Biodiversity Index was highest in Zone 4, closest to the land (Figure 8). This suggests that more species are suited to occupying niches with high protection and low inundation rather than unprotected and highly inundated niches. If this holds true, climate change may be detrimental to Misali's biodiversity, as it will bring more aquatic ecosystems and higher inundation.

Zonation

Forest A displayed significant zonation in mangrove forests. The zonation was found from sea to land (north to south in Forest A) as follows: *S. alba, R. mucronata, A. marina, B.*

gymnorrhiza, X. moluccensis. The specific niche of each species was supported by Forests B, C, and D.

At the unprotected edges of Forest, *S. alba* was found to be the first mangrove species present at the seaward side of most transects (Figure 9). In Forest B, *S. alba* also occupied a highly exposed zone and blocked other species from high energy wind and wave action. This suggests that *S. alba* is adapted and equipped to handle wind and wave action is ways that other species are not. In a study performed in Japan, Sun et al. (2004) studied the unique secondary xylem of *S. alba* species. While the main finding of the finding was that the xylem provided radial water transport, it was also found that this xylem provides extra strength to the tree and roots, boosting the mechanical strength of the tree itself. This additional strength could explain why *S. alba* is the most adapted to occupation of the most exposed niche in the forest.

The next layer of mangrove trees was *R. mucronata*, occupying areas with some protection from either coral rag or large *S. alba* trees while still highly inundated (Figure 9). The clustering of *R. mucronata* as well as the placement in the forest suggests that this species prefers slight protection while still requiring high inundation. Kathiresan and Rajendran (2004) found that *R. mucronata* commonly dwells in muddy substrate typically near *S. alba*, which holds true for Forest A on Misali Island.

P. acidula was found only on a 10 m tall coral rag boulder (Figure 9). In Forest B, *P. acidula* was also found growing atop a 10 m coral rag boulder on a much larger scale. *P. acidula* was also found along almost the entire border of Misali Island atop a 3-5 m coral rag wall. The location of this species in Forest A, Forest B, and around Misali suggests that *P. acidula* is not adapted to any amount of inundation but highly adapted for wind action. *X. moluccensis* fell at the far east end of the forest on the cusp of the terrestrial vegetation (Figure 9). This could be a result of the species preferring low inundation and possibly drier and rockier soils than the mud of Forest A.

A. marina also displayed zonation patterns, tending to fall in the landward side of the transect and habituating areas of the forests that got the least wind and wave action exposure (Figure 9). In addition, *A. marina* was also observed living on beachfronts along the perimeter of the island. Kathiresan and Rajendran (2004) found that *A. marina* prefers sandy substrates, explaining why the *A. marina* was located closest to the beach of Forest A and decreased in number as the substrate got muddier. *A. marina* was also observed in and around the beaches of Misali Island, occupying the niche of the seaward fringe, displaying similar zonation patterns of *A. marina* found by Fujimoto & Miyagi (1993) in the Federated States of Micronesia and Dahdouh-Guebras et al. (2002) on the Kenyan coast.

Given that there was only one *B. gymnorrhiza* tree present, it is difficult to draw conclusions about the zonation preferences of this species. However, Kathiresan and Rajendran (2004) report that the species *B. gymnorrhiza* prefers wet areas away from the open coast, which may explain why only one tree survived to adulthood in this instance, but most seedlings did not.

While mature *C. tagal* was not present in Forest A, it was found on other parts of Misali, including in Forest B, C, and D. While there was only one tree present in Forest B (the most exposed as it is only protected on one side), there were approximately five found in Forest D and 50 found in Forest C. Due to Forest C being based around a small estuary running inland from the ocean, it was highly protected yet provided sufficient inundation, explaining why *C. tagal* is able to thrive there. These results suggest that while *C. tagal* is adapted to levels of inundation, it needs significant protection from wind and wave action, preferably by coral rag boulders. In addition, the results from Forests A and D indicate that *C. tagal* might be outcompeted by *A.*

marina. This is supported by the observation that the forest with the highest count of *C. tagal* (Forest C) had no *A. marina* and the forest with the highest count of *A. marina* had no *C. tagal*. Another factor is that *C. tagal* prefers to reside in drier areas (Kathiresan & Rajendran, 2004; Semeniuk, 1994)

X. moluccensis lay on the southern edge of the forest between the mangrove forest and the terrestrial forest. While there is no zonation information about the preferences of the species *X. moluccensis*, Kathiresan and Rajendran (2004) report that *X. granatum*, in the same family as *X. moluccensis*, is often associated with landward fringe.

The zonation ranking of three for Forest A suggests that the existing zonation will contribute to the success of mangrove forests on Misali Island. Aquatic species such as *S. alba* and *R. mucronata* will likely continue to thrive in inundated areas while terrestrial species such as *C. tagal* and *P. acidula* will continue to migrate landwards.

Reproduction

Mangroves are some of the few plant species which have viviparous reproduction, meaning that they give birth to live young, like mammals. In trees, vivipary means that the embryo of the young plant breaks through both the seed wall and fruit wall while still attached to the parent tree (Lim et al. 2001). Different mangrove species have varying levels of vivipary; *R. mucronata* develops extensively while on the parent tree while *A. marina* develops to a lesser extent, only breaking out of the seed wall before the propagule is released, called cryptovivipary (Lim et al., 2001). Varying vivipary levels might explain why *R. mucronata* seedlings seem to be more successful than *A. marina* seedlings in Forest A, as *R. mucronata* drops seedlings that are more developed than *A. marina* seedlings, giving them an advantage in competition. Instead, *A. marina* and *S. alba* rely more heavily on regeneration from roots and fallen stems (Fuijmoto &

Miyagi, 1993). In addition, the mortality of *R. mucronata* seedlings is lower than that of *A. marina*, meaning that more *R. mucronata* seedlings survive to adulthood (Booker et al., 1998). This also provides an explanation as to the high number of *R. mucronata* seedlings and low number of *A. marina* seedlings.

Reproduction proved to be a challenging factor to measure given that not all mangrove species can be measured for success based on the seedling count, in particular, *A. marina* and *S. alba*. For example, *R. mucronata* seedpods produce roots in approximately 15 days while *A. marina* propagules produce roots in about seven days (Booker, 1998). In addition, the reproductive cycle of *R. mucronata* takes about 16-20 months while that of *S. alba* take only four to five months, which is comparatively about one fourth of the time (Wang'ondu et al., 2013). Rather than producing a large number of semi-successful propagules like *R. mucronata, A. marina* produces few propagules which are highly successful (Burns, 1985). Given these factors, *A. marina* propagules could be thought to be more successful once in seedling form, as they take root faster and have a higher success rate. Another factor which may play a role in the varying seedling and sapling count is seasonality. A study performed in Gazi Bay, Kenya, found that *R. mucronata* was able to reproduce almost year-round, while the reproduction cycle of *S. alba* was heavily dependent on seasonal factors, such as amount of rainfall (Wang'ondu et al., 2013). Due to the variety of factors that play into a species' reproductive success, it is problematic to simplify this complexity and compare all species based explicitly on seedling count.

In addition, this ranking system only accounts for the number of young trees but fails to account for success rate beyond the sapling stage. Burns and Ogden (1985) found that the primary determinant for population growth was the success of young trees, while seed production of trees was relatively insignificant. For example, 32 seedlings of *C. tagal* were found in Forest A, but zero saplings and zero adult trees (Table 1). While the ranking system used in this study deems *C. tagal* reproductively successful, the lack of adult trees shows that the species is outcompeted at the seedling or sapling level which reduces its survivorship to adulthood. This suggests that *C. tagal* is actually highly unsuccessful (in terms of producing seed-bearing adult individuals) in this particular forest. However, the lack of adult *C. tagal* in Forest A does not correlate to Forests C and D, in which *C. tagal* had high counts of both adult trees and young. These comparisons suggest that *C. tagal* is more terrestrial-based, with greater success in coastal fringing forests than in overwash forests, and therefore only measuring the success rate in one type of forest is an inaccurate representation of the species. The lack of adult success in Forest A may be due to seedling competition with species typically found in overwash forests such as *R. mucronata* and lack of protection.

It is impossible to reduce the complexity of reproductive success in mangrove forests down to a number which can be ranked on a scale. An alternate way to study the reproductive success of mangrove species would be to consider both the number of seedlings produced as well as the number of propagules that survive to adulthood.

Conclusion

Given the biodiversity, zonation, and reproduction results, mangroves on Misali Island are adaptable enough to survive on Misali. While there is no way to measure the length of time they will be resilient, the mangroves of Forest A, B, C, and D display promise for their persistence on the island. Based on the results of zonation and reproduction, *R. mucronata* will be the most successful species in the future of Misali's mangroves. This is due to this species' ability to survive in highly inundated environments as well as its high reproductive success rate.

Aquatic species adapted to high exposure such as *S. alba* and *A. marina* also show promise in their ability to adapt to sea level rise and heightened storm action. In terms of reproduction, *C. tagal* and *B. gymnorrhiza* might stand the best chance of maintaining a population but will suffer if sea level rise causes inundation to the drier ecosystems of the island where these species typically dwell. *P. acidula* displays potential with its hardiness and resistance to high exposure to wind action but will fail if the island goes underwater in the future.

The overwash mangrove forest has the greatest potential for adaptability. The species occupying overwash niches are the most adaptable to wind and wave action as well as inundation; processes that climate change models expect to intensify in the future. While scrub forests are vulnerable to inundation, they will be the last to be inundated, so they will likely persist for a while in the future. Coastal fringing forests may be the first to perish. These forests are composed largely of species most vulnerable to wind and wave action and that prefer sheltered and protected environments. With impending sea level rise and heightened storm action, coastal fringing forests may not be able to withstand these intense circumstances.

With these predictions, Misali Island may be better equipped to create a management plan for the future of its mangrove forests. Knowledge that overwash forests may be the most adaptable could aid the government of Tanzania and rangers of Misali in prioritizing forests for protection.

Recommendations

Throughout this study, I faced challenges with data collection and working in the field. One challenge was laying transects through the mangrove forest. Complex and dense root system, mainly stemming from *R. mucronata,* made laying straight and flat transects difficult.

Though a compass was used in order to maintain a straight bearing in the forest, the transect could not always be laid according to the bearing due to root masses or tree branches. Another challenge was dealing with the shape of the overall forest in Forest A. As transects were laid perpendicular to the shoreline and the shoreline was curved, the transects were not parallel and therefore did not have an equal amount of spacing between them. Due to this challenge, some trees may not have been surveyed while a few others may have been surveyed twice.

While the focus of this study was on biodiversity, zonation, and reproductive success as measures of adaptability, there are other factors affecting the success of mangrove forests on Misali Island. One factor that could be studied is the root systems of various mangrove species. Many species have aerial roots which is an adaptation to the anaerobic nature of the mud substrate that exists in many mangrove ecosystems. These roots types include pneumatophores, prop roots, stilt roots, knee roots, and plank roots, all of which have different adaptations and capabilities (Lim et al., 2001). A future study might consider root structure as an adaptive capability of mangroves and look into which species might be best equipped to handle rising sea level based on root structure alone.

Another factor which may contribute to the adaptability or vulnerability of mangrove forests in the face of climate change is sediment accretion rates. Given the high sedimentation rates in mangrove ecosystems, mangroves substrates continue to compound vertically and, in effect, keep up with an increasing sea level. A study performed in Cameroon shows that net sedimentation rates were just below net sea level rise predictions (Ellison & Zouh, 2012). Another study shows that root density is positively correlated with accretion rates (Krauss, 2013), meaning that the measure of root mass on Misali Island could predict accretion rates at present and into the future. The exact rate of accretion underlying a forest may determine its success with rising sea level, making this an important factor of study on Misali Island.

Finally, anthropogenic factors that impact the mangrove forests on Misali must be studied to capture the full complexity of Misali's mangroves. Though it is illegal to extract mangroves in the Zanzibar Archipelago, Misali Island included, a high count of stumps was observed in Forest A (Appendix A). If significant cutting continues, the forests on Misali will suffer regardless of the effects of climate change.

The government of Zanzibar could use this study to develop an appropriate and useful management plan for not only the mangrove forests of Misali Island, but those of the entire archipelago. By understanding which mangrove species and forests are most vulnerable, the government and people of Zanzibar and Tanzania could work to protect and rehabilitate forests at risk.

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Appendix

A.