Coral Health Thrives in Unprotected Reef Ecosystems in Southeast Nosy Be, Madagascar

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ABSTRACT

The coral reefs in Madagascar hold a special importance in the Indian Ocean. The country is among the top 15 in the world for largest coral reef area, and it shelters the greatest diversity of corals and macroinvertebrates in the central and western Indian Ocean. Because of their importance to marine ecosystems, research and protection of these threatened areas is imperative. The objective of this study was to assess the nature of hard coral reef ecology in the southeast region of Nosy Be and to better understand the extent of coral bleaching and disease as it compares to past conditions. The method I used to assess live hard coral cover and coral composition was benthic survey methodology. Across 5 different sites around southeast Nosy Be, the presence of health conditions such as bleaching, diseases, algal assembly, and soft coral colonization was collected, and coral cover and taxonomic composition was collected and calculated. Results show that coral cover and biodiversity have increased in certain sites and that counts of health conditions at every site were low compared to each site's coral cover and to past results found in 2015. These findings suggest that the overall health of corals around Nosy Be has improved and that the unprotected reefs around Lokobe National Park are likely comparable in coral cover than those protected sites. Accounts say that local communities have stopped disturbing their nearby reefs and have begun supporting and enacting regeneration projects at certain reefs on the island, ending anthropogenic disturbance as a health detriment and aiding the reefs in recovery and survival. More research, attention, and action should be placed on all fragile ecosystems in Madagascar, and the responsibility should be on the Malagasy government to look into establishing the presently studied sites as protected areas to ensure their continued success and survival.

Les récifs coralliens de Madagascar ont une importance particulière dans l'Océan Indien. Le pays figure parmi les 15 meilleurs au monde de pour la plus grande zone de récifs coralliens, et il abrite la plus grande diversité de coraux et de macroinvertébrés du centre et l'Ouest de l'Oéan Indien. Au cause de leur importance pour les écosystèmes marins, la recherche et protection de ces zones menacées sont impératives. L'objectif de cette étude était d'évaluer la nature de l'écologie des récifs coralliens durs dans la région Sud-Est de Nosy Be et de mieux comprendre l'étendue du blanchissement et de la maladie des coraux par rapport aux conditions passées. La méthode J'ai utilisé pour évaluer la couverture des coraux dur vivant et la composition de la couverture de corail était la méthodologie d'étude benthique. Sur 5 sites différents autour du Sud-Est de Nosy Be, la présence de conditions de santé telles que le blanchissement, les maladies, l'assebmlage d'algues et la colonisation des coraux mous ont été collectées et la couverture corallienne et la composition taxonomique ont été collectées et calculées. Les résultats montrent que la couverture corallienne et la biodiversité ont augmenté dans certains sites et que le nombre de conditions de santé sur chaque site était faible, comparable à la couverture corallienne de chaque site et aux résultats antérieurs trouvés en 2015. Ces résultats suggèrent que la santé globale des coraux autour de Nosy Be a amélioré et que les récifs non protégés autour du Parc National Lokobe sont probablement comparable en termes de couverture corallienne à deux des sites protégés. Les comptes disent que les communautés locales ont cessé de perturber leurs récifs voisins et ont commencé à soutenir et à mettre en œuvre des projets de régénération sur certains récifs de l'île, mettant fin aux perturbations anthropiques comme un préjudice pour la santé et aidant les récifs à se rétablir et à survivre. Plus de recherche, attention, et action

devraient être accordées à tous les écosystèmes fragiles de Madagascar, et la responsabilité devrait incomber au gouvernement Malagasy pour qu'il envisage d'établir les sites actuellement étudiés en tant qu'aires protégées afin d'assurer leur succès et survie.

Introduction

Coral Reef Biology and Ecology

Coral reefs are shallow-water marine ecosystems that host a large diversity of sea-life. These environments host about 25% of all marine life, and the coral reefs in Madagascar specifically hold a special importance in the Indian Ocean. Madagascar is among the top 15 countries in the world for largest coral reef area, and it shelters the greatest diversity of corals and macroinvertebrates in the central and western Indian Ocean as well as high species richness of shellfish and fish (Jadot et al., 2015). Because of these reefs' importance to marine ecosystems, it is important to continue research and protection of these threatened areas.

Unlike other animals, Cnidarians — and corals in particular — display an incredibly unique biology that differs from the common conception of life in the animal kingdom. While some corals are free-living individuals, many corals form in colonies, making the distinction between each individual impossible (Allen-Waller, 2015). As such, benthic surveys, which mark contacts on meter-markers rather than counting individuals, are more appropriate in coral research. On the skeletal level, corals form corallites, crater-shaped pores on the surface of the coral that come in different varieties: some have well-defined walls visible underwater, and some have no walls at all where corallites blend into each other (Indo Ocean Project). Live tissue grows on the top of the corallites forming polyps, which have tentacles, mouths, and a gut. Polyps can appear a different color than the rest of the tissue, aiding in identifying the taxonomy of the coral underwater. Hard corals have tentacles in multiples of 6 and grow both in colonies and solitarily, such as in Fungia. They are the main reef builders as opposed to soft corals and create limestone skeletons in their construction. Their skeletons mostly remain after death, creating an ideal breeding ground for algae and soft corals. Corals grow in various forms, and multiple are possible for colonies of the same species: arborescent, caespitose, corymbose, digitate, tabular, columnar, massive, foliose, solitary, and encrusting.

There is also a diversity within the structure of different taxa, including solitary attached corallites, plocoid, cerioid, thamnasteroid, and phaceloid. The unique structures of a colony and the form it takes is key in identification. Corals live in symbiosis with the reef environment around them. Their skeletons, dead or alive, provide breeding grounds for algae and soft corals and provide shelter and homes for various other reef populations and species (Indo Ocean Project). In addition, corals display symbiosis with zooxanthellae, microscopic algae that live on the surface of live coral and engage in a nutrient exchange using photosynthesis that help the corals feed while giving them their color. Figure 1 shows Cnidarian host immune pathways in three stages of symbiosis.

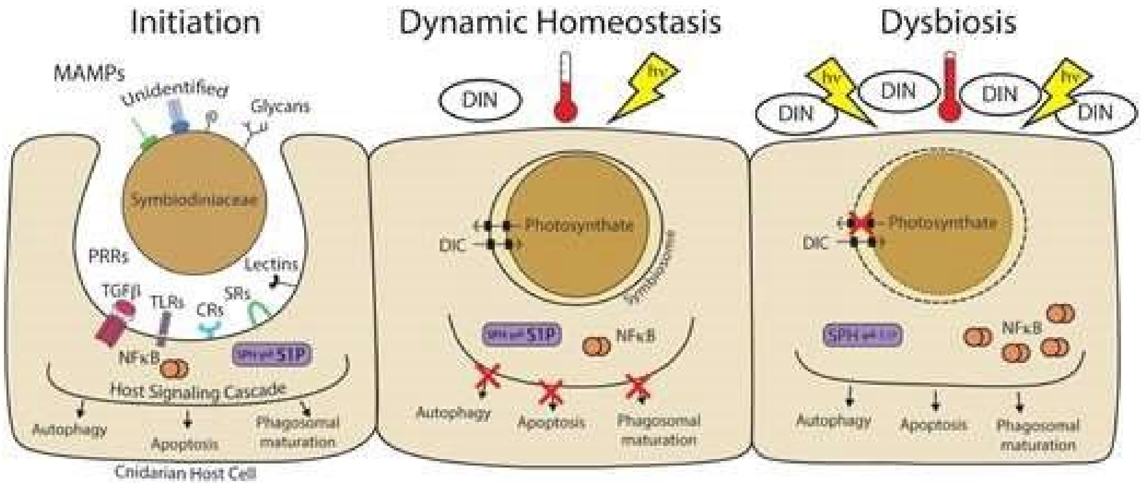

Figure 1. Schematic diagram depicting the three phases of symbiosis in Cnidarian host innate immune pathways. Initiation (left), dynamic homeostasis (middle), and dysbiosis (right). Initiation: Symbiodiniaceae have various MAMPs along their surfaces, which interact with Cnidarian gastrodermal cell PRRs. MAMP-PRR interactions modulate a series of signaling cascades that lead to microbe destruction. An appropriate Symbiodiniaceae will modulate the immune response and will persist inside the host symbiosome. Dynamic homeostasis: During stable symbiosis, at ambient temperature, normal light levels and low dissolved inorganic nitrogen (DIN), the symbiont and host cell exchange nutrients where the host passes dissolved inorganic carbon

(DIC) to the symbionts which in turn fix the carbon by photosynthesis and pass it back to the host as photosynthate. The symbiont is stable because the host innate immune pathways are inactive and tolerogenic. Dysbiosis: elevated temperature, high light, and excess DIN result in cessation of photosynthate transport into the host. In this reengaged immune system response, the host eliminates the stressed symbiont. Processes depicted here are described in Weis (2019).

Bleaching

Coral reefs are threatened by rising ocean temperatures which cause stressors in corals that, if unsolved, ultimately lead to coral death. By the end of the century corals face almost complete destruction unless humans keep global warming to a maximum of 1.5 degrees Celsius above pre-industrial levels, when the global temperature was 1.06 degrees cooler (Weis 2019; Lindsey, Dahlman, 2023). In order to cap the rise at 1.5 degrees, humanity must change its behavior before 2030 (Weis 2019). Along with rising ocean temperatures, extremely low tides, pollution, and too much sunlight may also cause bleaching (Hancock, WWF).

Once corals die, reefs rarely come back. When populations dwindle and reproduction fails, entire reef ecosystems on which people and wildlife depend are lost. Just between 2014 and 2017, around 75% of the world's tropical reefs experienced heat-stress severe enough to trigger bleaching and 30% of all corals worldwide died (Hancock, WWF).

Thousands of marine faunae depend on coral reefs for survival, including sea turtles, fish, crabs, shrimp, jellyfish, sea birds, and star fish. For these animals corals provide shelter, breeding grounds, and protection from predators (Hancock, WWF). When coral reefs collapse, already endangered species face the possibility of extinction. Humans too depend on coral reefs. Barrier reefs act quite literally as barriers that absorb the force of waves and storm surges, keeping coastal communities safe. Bleached coral removes links in the food web and deprives some fish and crustacean species a place to spawn and develop (Hancock, WWF). This means that communities who depend on these animals as a source of income or food are threatened by the effects of bleaching and climate change. Coral reefs also bring in billions of dollars each year in reef tourism that also supports thousands of jobs.

Coral Diseases

Coral diseases cause substantial decline in the biodiversity and abundance of reef-building corals (Séré et al., 2015). More than 30 distinct diseases have been reported that cause tissue loss or that affect growth and lower reproductive capacity, recruitment, and coral species diversity. However, not very much is known about coral diseases, which is why its research is vital to our understanding of threats to corals in the world. Among the many diseases, the most prevalent in southeast Nosy Be are described in Table 2 in Methods.

Pathogenic and environmental disturbances cause higher disease rates, which means that while climate change worsens — sea temperatures rise, oceans acidify, turbidity increases — disease counts will rise, taking advantage of vulnerable hosts and making corals more threatened (Allen-Waller, 2015). Sedimentation and nutrient enrichment have also been shown to increase the frequency and severity of disease outbreaks (Bruno et al., 2003; Sheridan et al., 2014; Aeby et al., 2021). The most vulnerable corals to diseases by genera are Acropora and Porites, which are the most common reef-building corals in southeast Nosy Be (Aeby et al., 2021; Allen-Waller, 2015).

Algal and Soft Coral Colonization

Red algae, brown algae, and green algae are macro-algal species that grow out of and replace seagrasses and corals reef habitats (Swierts & Vermeij, 2016). The degradation of tropical reefs through human-driven disturbances leads to a decline in reef-building corals and an ideal breeding ground for macroalgae, demonstrating that anthropogenic disturbance increases algal colonization in coral reefs (Brown et al., 2018). While diseases may be linked to seasons of the year, algal colonization persists at consistent levels throughout all seasons (Brown et al., 2018). However, not all coral-algal interactions are harmful to corals. In the case of micro algae like zooxanthellae, corals exhibit a symbiotic relationship, depicted in Figure 1. Further, the frequency of coral-algal interactions is dependent on the health and vulnerability of the coral, not just on macro algal cover, and an increase in coral-algal interactions does not necessarily translate to degradation of coral reefs (Brown et al., 2018). It is also known that some growth forms of corals, such as branching corals who grow above and out of the benthos have a higher likelihood of avoiding interactions and colonization by turf algae, while non-erect growth forms like encrusting and massive corals are less likely to escape such interactions (Swierts & Vermeij, 2016). While coral-algal interactions can be harmful and inescapable, they are not necessarily a threat to the reef as a whole (Brown et al., 2018).

Soft corals are similar to hard corals in that they provide shelter, safety, and breeding grounds for different tropical fish species, but different in that they rarely act as reef builders since they have no limestone skeleton and no skeleton remains after death (Indo Ocean Project). While soft corals, like hard corals, bleach when stressed, their resilience to the phenomenon is higher than that of hard corals (Hawley, 2022). In marine heatwaves, soft corals like Xenia were found to respond by acquiring more, not less, symbionts, exhibiting a reverse stressing affect due to high temperatures. Because of these soft corals' success under stress, it would be likely that in corals reefs where stressors are frequent and high, hard corals will suffer and soft corals will prosper, eventually colonizing over vulnerable reef-building corals and deteriorating the reef. Alternatively, it's possible that re-colonization of soft corals on a degraded reef could potentially save the reef from total loss (Chandran et al., 2015).

Objectives and Hypotheses

The objective of this study is to assess the nature of hard coral reef ecology in this region of Nosy Be and to better understand the extent of coral bleaching and disease as it compares to past conditions. In understanding the condition of coral health in this high-tourism reef area, Nosy Be, one can better understand the imminence of climate change as it threatens coral reef ecosystems. Another major objective of the study is to observe what differs between reefs that are in close proximity to freshwater outputs, clear of freshwater outputs, in close proximity to human presence and civilization, and farther from human contact.

In 2015 Allen-Waller surveyed five protected sites in Lokobe National Park and one site on Nosy Komba, retrieving data about hard coral cover at each site and taxonomic and spatial variation and such data for bleaching, disease, and colonization counts. Using the same methodology and performing the survey at the same one site on Nosy Komba and one site close to Lokobe, my study aims to retrieve data comparable with that of Allen-Waller in order to draw distinct temporal comparisons of coral health. At the time of my study, the time elapsed is about eight years, from 2015 during Madagascar's dry season until 2023 at the end of the wet season.

It is hypothesized foremost that the total occurrence of coral bleaching will be higher than in 2015, since global sea temperatures have risen and annual cyclones persist and at a higher magnitude and rate than previously (NOAA 2023). While the timing of this study gives the coral enough time to have recovered since 2015, it is expected that some counts of coral bleaching will either relatively match or exceed the results from that time

(Wolanski 2019). Similarly, it is expected that disease and soft coral and algal colonization will be higher than in 2015 since bleached and vulnerable corals are optimal breeding grounds for algae and soft coral species (Ravindran et al., 2012). Allen-Waller also found that the site on Nosy Komba had one of the lowest coral covers of all the sites and it had the most disease, which was likely due to anthropogenic disturbance (Allen-Waller 2015). It is thus hypothesized that coral cover will be low, if not lower, than the initial study and will have higher counts of disease due to ongoing anthropogenic disturbance, and it will have more instances of bleaching due to sea temperatures and its correlation to the Allen Coral Atlas's projection of bleaching in this site (Figure 2). Additionally, it is expected that the counts of bleaching, disease, and colonization will be higher at CNRO, where the reef is in close proximity to one of the island's biggest cities which also has high sea traffic due to its being the main port city of Nosy Be.

Finally, it is hypothesized that in Nosy Komba there will be higher counts of the genera Acropora and Porites and fewer of the less common taxa described in the initial study since rising temperatures threaten biodiversity and the most common taxa will be more or relatively the same in abundance while the less common taxa will be lower in abundance. In Ambolifary where Allen-Waller found only Acropora and Porites, it is expected that there will be a higher coverage of Acropora than Porites since the former is more common across all oceans globally (United Nations 2023). Such genera described in the initial study range in their degrees of vulnerability globally, mostly airing on the side of not threatened, but all of them are decreasing, and it's possible that the individuals in southeastern Nosy Be are more vulnerable than the global average (IUCN 2023). Overall, it is hypothesized that all sites will be in relatively worse condition than sites studied in 2015 because previous sites were mostly localized within a protected area and the sites studied in this survey are all unprotected, and it's expected that anthropogenic disturbance will have worsened the condition of the reefs outside Lokobe. However, percent coral cover is expected to be higher than the previously studied sites in Lokobe as Allen Coral Atlas projects a higher cover of living coral and algae around the bay of Hell-Ville and to the west as compared with that of Lokobe's marine sites.

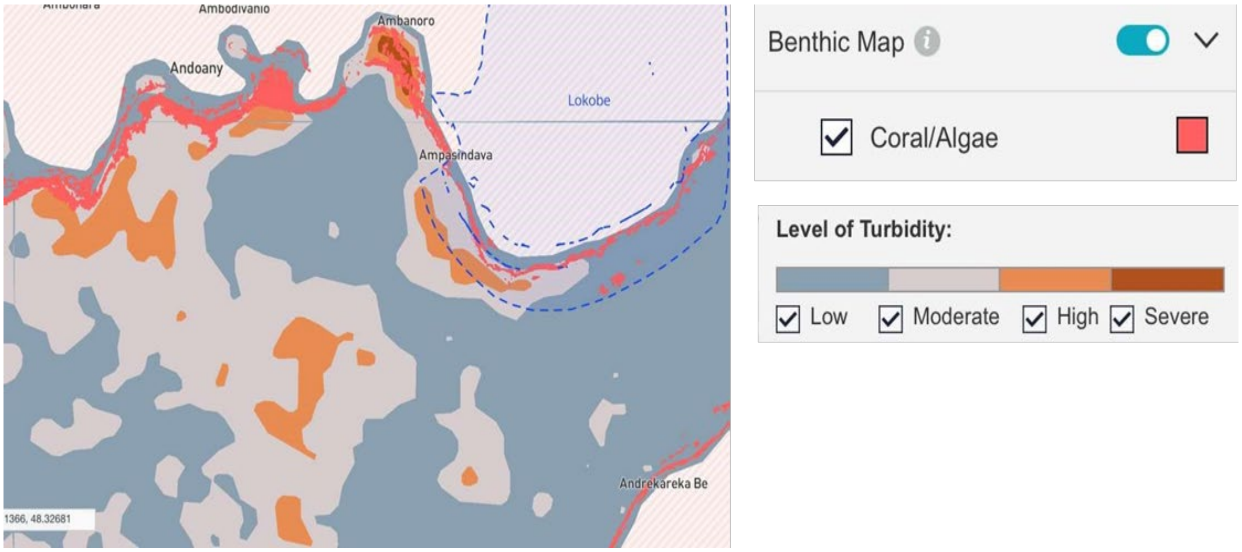

Figure 2. Map showing presence of coral around southeast Nosy Be, including also turbidity. Benthic layer showing corals in pink is up to date, and turbidity is averaged from the first quarter of 2023. The area in blue is Lokobe National Park, and all marine areas within its bounds are protected. These areas have smaller slivers of pink lines with low to moderate turbidity while the reefs to the west have larger pink zones and more turbid waters.

Methods

Localization

Five sites across southeast Nosy Be and Nosy Komba were selected for study, all lying outside of marine protected areas. Southeast Nosy Be is known for its Parc National Lokobe, a large tropical forest constituting the majority of the southeastern peninsula of the island. While the park provides guided tours around the forest to see families of Black Lemurs and a species endemic to Nosy Be, Hawks' Sportive Lemur, the park also protects a thin line of marine sites just off its coasts. As shown in Figure 2, however, the benthic coral cover of reefs within these protected boundaries are significantly lower than reefs to the west. As such, survey of coral cover and health in these unprotected areas around Lokobe National Park is required to analyze the need for protection in potentially more valuable or vulnerable reefs on the island. The following five sites were selected for study in Table 1: CNRO, Ambolifary, Andrekareka Be (Nosy Komba), Doany, and Ampandoma.

Table 1. Marine sites studied in the survey. Site name is given along with its coordinates, variability of depth and variability of visibility on the day of data collection. Site details came from observation and satellite imagery.

Site Name	GPS Coordinates	Depth (m)	Visibility (m)	Site Details
Ambolifary	S 13° 24'30.9679" E 48° 18'06.6258	2 to 3	3	Adjacent to habitation, adjacent to Lokobe MPA, close to freshwater outflow
CNRO	S 13° 24'30.9233" E 48° 17'10.531	2 to 5	4	Adjacent to uninhabited shore, close to large inhabited city

Ampandoma	S 13° 22'44.6059" E 48° 20'57.5434"	1 to 3	3	Not close to human habitation, exposed to open sea, adjacent to sea-grass ecosystem
Doany	S 13° 24'30.1165" E 48° 21'38.8674"	2 to 3	5 to 6	Far from human habitation, exposed to open sea, close to sea-grass ecosystem
Nosy Komba (Andrekareka Be)	S 13° 27'05.0" E 48° 19'39.6	3 to 5	8 to 9	adjacent to human habitation

Figure 3. Map showing survey sites and the port of departure for each day of data collection. Six blue pins mark the five sites of survey, including four around southeast Nosy Be and one from Nosy Komba, and one pin for the port from which the research vessel departed for each day of data collection. Not shown: Hell-Ville, Nosy Be's port city, lies just west of CNRO. © 2023 Google maps.

While no sources have confirmed that Nosy Komba has been established as a protected area, "Madagascar

Volunteer" claims that the island's reefs have become protected (MRCI, 2019). According to Madagascar Protected Areas, the only protected site in the Nosy Be area is Lokobe National Park (2023). It is possible, however, that local communities have started to protect their reefs and aid in its conservation and regeneration, as is the case for the two sites east of Lokobe, Doany and Ampandoma, whose reefs are young and newly regenerated by local populations according to CNRO's director Adouhouri Aly Bachiry.

Benthic Survey and Coral Composition

The method used to assess live hard coral cover and coral composition was benthic survey methodology. Using a 50m tape measure, a 20-meter line of transect was measured along the benthos of a reef. Along this line, the locations and genera of all living hard corals were recorded. I performed coral identification on sight, using several internet sources to obtain skills and readiness to identify hard corals of the western Indian Ocean (Helgason, 2018; Corals of the World; Indo Ocean Project). When coral genera were unknown, photos were taken with an underwater camera and assessed using the image, known specific physical traits of the coral, and internet sources to identify them after data collection. Data taken in the sea were all written on underwater tablets and copied into a waterresistant notebook on the boat. Coordinates were recorded using Google Maps. Within 100 m of the coordinates taken for each site, this method was performed four times. Hard coral cover for each site was calculated by presence/absence of coral contact at each meter of the line of transect, averaging the four stations. Coral composition by genera was calculated by genera percent abundances over the overall coral cover of each station, averaging the four stations.

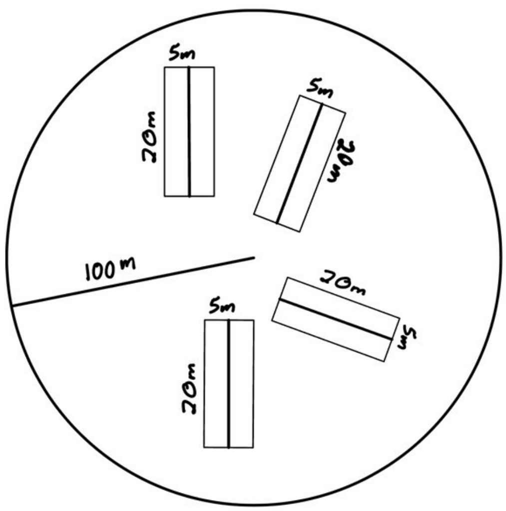

Figure 4. Drawing depicting benthic survey methodology. Not shown: research boat would be in the center of the circle. Research stations spanned within a 100m radius of the boat, making sure not to intersect previous stations.

Bleaching, Diseases, and Opportunism

Incidents of coral health conditions were categorized into bleaching and a range of diseases and colonization depicted in Table 2 (Allen-Waller, 2015). The table is replicated from Allen-Waller's study in 2015 in order to make results from the current study comparable to the two sites that were studied in 2015, Ambolifary and Nosy Komba. Widening the line of transect of each station 2.5 m on either end, incidents of all health conditions afflicting live hard corals were recorded within the area as well as the genus of the afflicted coral, except in the case of soft coral and macro-algal colonization, where the tissue of the colonized coral was often not exposed, making identification unreliable and therefore impossible.

Table 2. A table of conditions used to categorize incidents of bleaching, disease, algal assembly, and soft coral colonization. Abbreviations were used to simplify data collection underwater and descriptions aid in onsite identification and post-collection analysis. Table is replicated from Allen-Waller, 2015.

Condition	Abbreviation	Broad disease category	Description
Bleaching	-	-	White, semitranslucent appearance of part or all of a hard coral (no lesions)
Algal assembly covering coral	AA	-	Filamentous algal growth covering partially or completely dead hard coral
Soft coral colonization	-	-	Soft coral growth covering partially or completely dead hard coral
White syndrome	WS	white syndrome	Acute to sub-acute lesions exposing skeleton
Pink spot	PS	pigmentation response	Acute to sub-acute lesions surrounded by a band of bright pink coral tissue
Violet spot	VS	pigmentation response	Acute to sub-acute lesions surrounded by discolored lavender coral tissue
Orange band	OB	pigmentation response	Acute to sub-acute orange lesions
Black band disease	BBD	pigmentation response	Sub-acute lesions surrounded by a band of dark, discolored coral tissue
Yellow band disease	YBD	pigmentation response	Sub-acute lesions surrounded by a band of pale yellow coral tissue
Porites ulcerative white spot	PUWS	other	Multiple small, discrete, acute, oblong white lesions
Tissue necrosis	-	other	Diffuse, somewhat darkened tissue loss with no pigmentation response

Disease rates by site were calculated using the number of incidents of disease at each site divided by the total area surveyed, 400m. Disease abundances were compiled using the broad categories in Table 2, while total abundances of specific diseases were calculated for Nosy Be (sites 1-4 on Table 1) and Nosy Komba (Andrekareka Be on Table 1) to compare disease diversity. Bleaching was evaluated by genera and by site, and algal and soft coral colonization were evaluated only by site on the basis of total incidents per site.

Results

Coral Cover and Composition

Andrekareka Be on Nosy Komba showed the highest percent of live hard coral (60%). No site was sententiously lower than the others except for Ambolifary (35%), which had the lowest coral cover. Ambolifary also had the lowest coral diversity, displaying only three genera with the vast majority consisting of Porites (89.89%). Overall, porites was the most abundant genus among all sites except Nosy Komba, where the most abundant was Acropora (64.68%). The relative abundances of other genera varied, but Favia was found on all sites except Ambolifary, Platygyra was found in all sites except Nosy Komba, and Galaxea was found only on Nosy Komba.

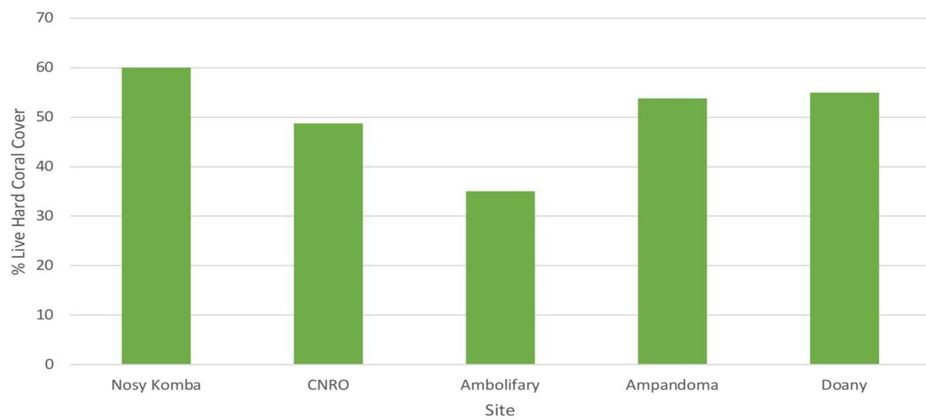

Figure 5. Percent live hard coral cover by site.

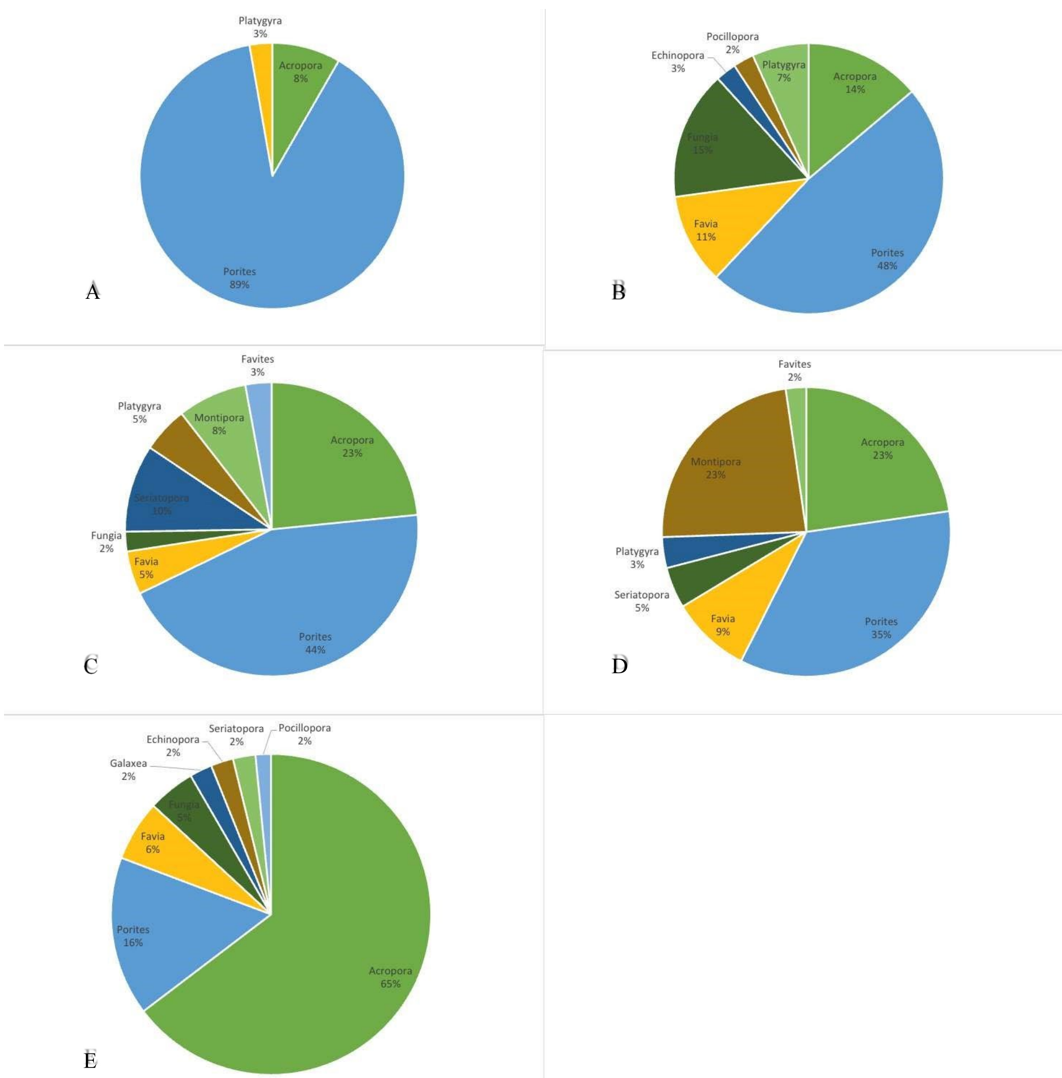

Figure 6. Relative abundances of coral genera at each site. A: Ambolifary, B: CNRO, C: Ampandoma, D: Doany, E: Nosy Komba.

Coral Bleaching

Thirty-eight occurrences of coral bleaching were found across all sites. Nosy Komba exhibited the most bleaching (20 incidents), where total counts more than doubled any other site. Ampandoma showed the fewest incidents of bleaching, followed by Doany. Additionally, bleaching only occurred to corals in the genera Acropora and Porites, with Acropora occupying the most incidents, especially on Nosy Komba, where bleaching counts were the highest. All incidents were taken in total areas of 400 square meters per site.

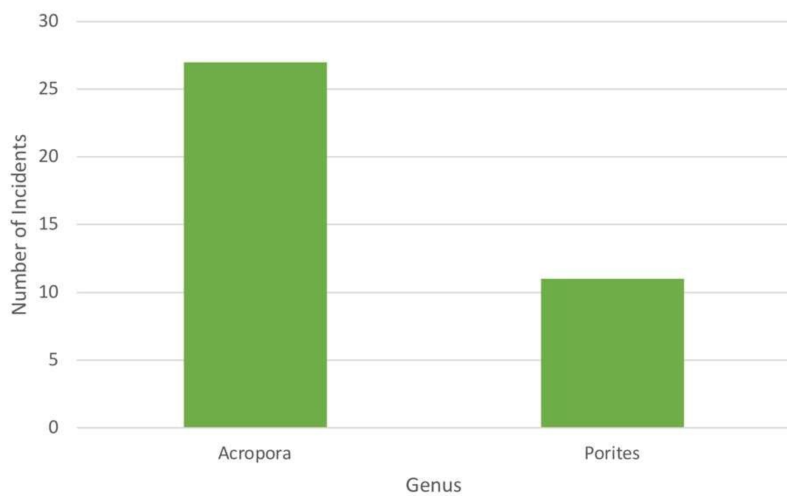

Figure 7. Total counts of coral bleaching by genus. Data was compiled and totaled across all sites.

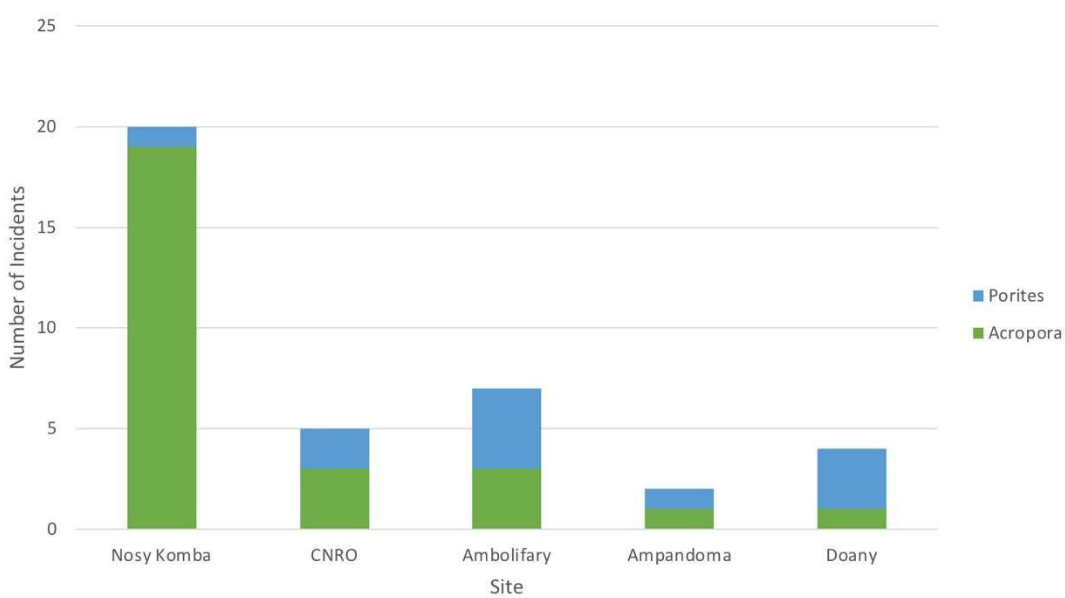

Figure 8. Coral bleaching by site. Both relevant genera are shown in green (Acropora) and blue (Porites).

Coral Disease

Coral disease counts totaled at 26 incidents, more occurring in Nosy Komba than all other sites combined.

The fewest occurrences of disease were in Ambolifary and CNRO, where only one total disease was recorded in the 400 square meter areas. The only genera found to be affected by diseases were Acropora, Porites, and Favia. The disease type and genus varied, but the most frequent broad term disease found across all sites was Porites pigment response. Only one site, CNRO, didn't exhibit Porites PR or Acropora PR, which was present in most sites as well. Between Nosy Be and Nosy Komba, more tissue necrosis occurred on Nosy Komba. Not every disease observed in Nosy Be also existed on Nosy Komba, and some diseases found on Nosy Komba didn't exist on Nosy Be. Finally, not every disease from the table of diseases (Table 2) existed in the surveyed sites.

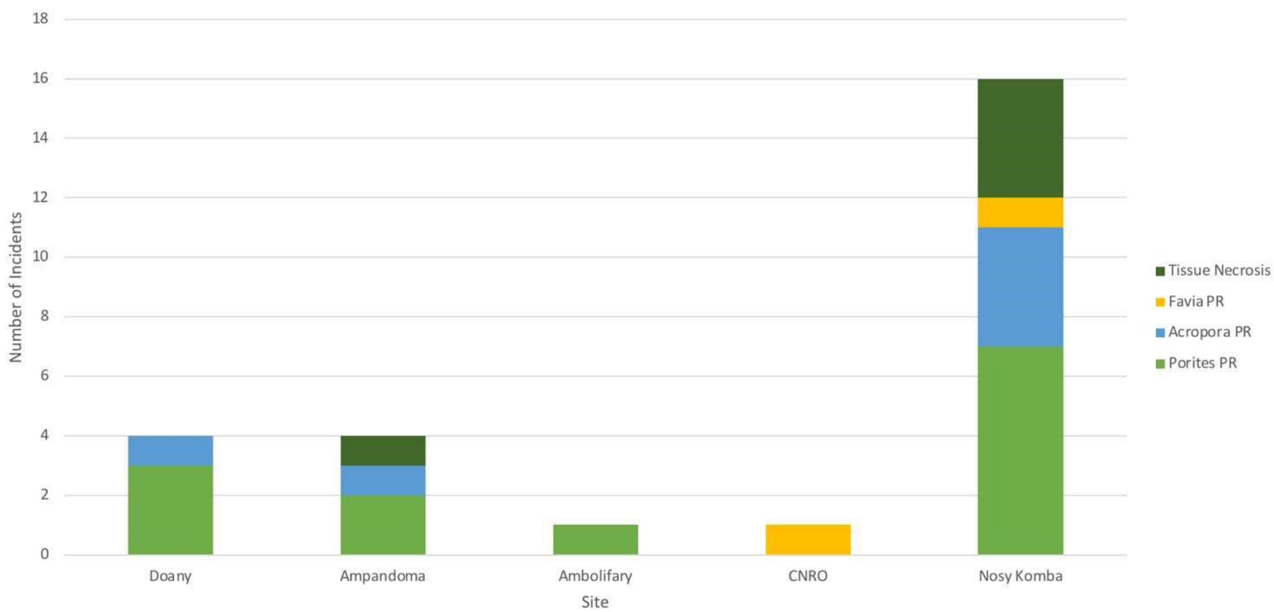

Figure 9. Incidents of disease by site. Diseases were simplified into broad categories, where PR = pigment response for each relevant genus and tissue necrosis is independent of genus.

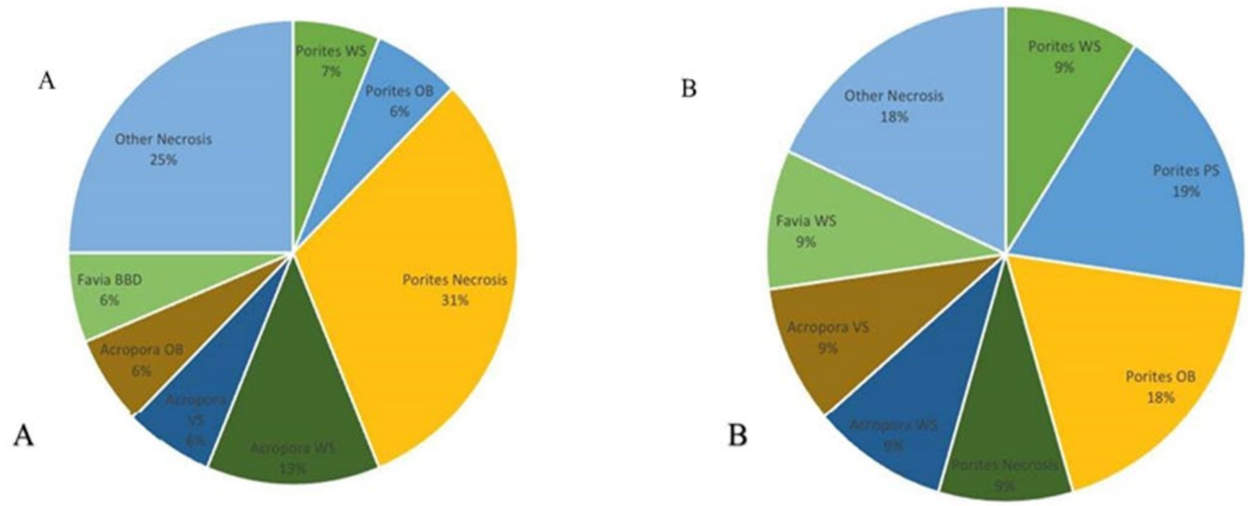

Figure 10. Relative disease abundance by island. Nosy Komba (A) data is compiled by the one site on Nosy Komba, Andrekareka Be, and Nosy Be (B) data is compiled by the 4 other sites surveyed. WS, White syndrome; OB, Orange band; PS, Pink spot; VS, Violet spot; BBD, Black band disease.

Table 3. Rates of occurrence for broad categories of disease across all sites. PR, pigment response.

Site name	Total Disease (incidents/ha)	Porites PR (Incidents/ha)	Acropora PR (Incidents/ha)	Tissue Necrosis (Incidents/ha)	Favia PR (Incidents/ha)
Doany	100	75	25	0	0
Ampandoma	100	50	25	25	0
Ambolifary	25	25	0	0	0
CNRO	50	0	0	25	25
Nosy Komba	400	175	100	100	25

Algal and Soft Coral Colonization

The surveys revealed a total of 47 algal assemblies on live hard coral across all sites. Algal assembly was significantly higher at Ampandoma than the other sites and was the lowest in Ambolifary. Soft coral colonization occurred a total of 23 times, the most occurring at CNRO and the least at Ambolifary. No soft coral colonization occurred on Nosy Komba.

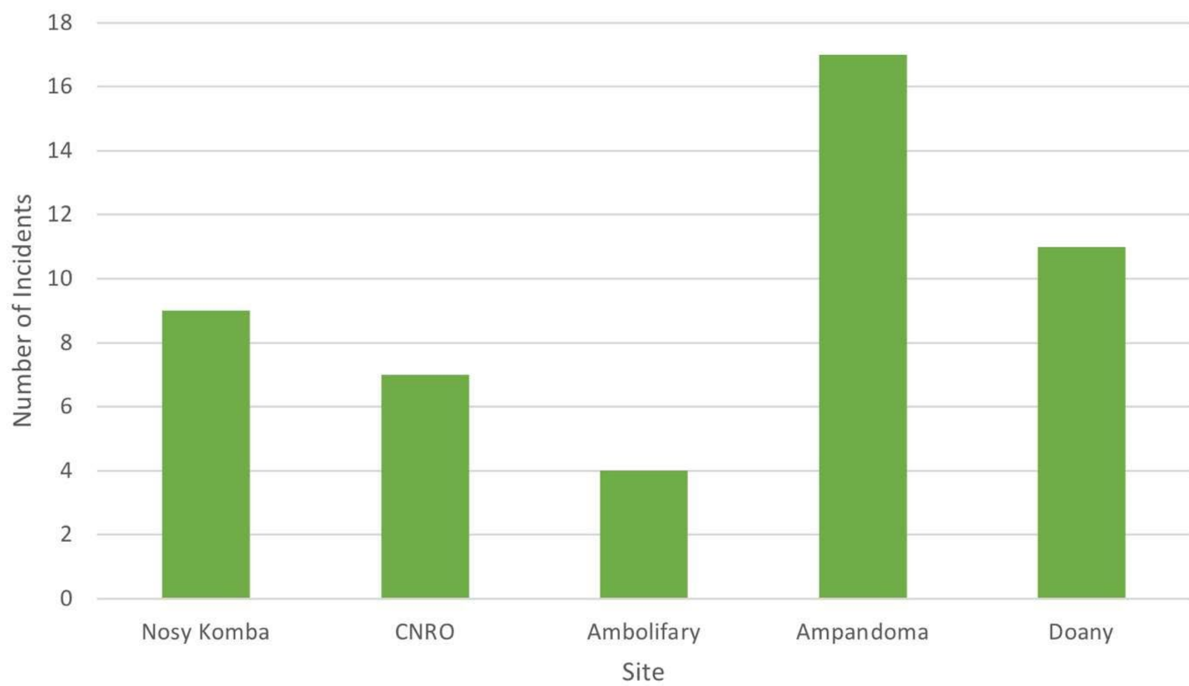

Figure 11. Incidents of algal assembly on hard coral by site. Area surveyed per site = 400 m^2.

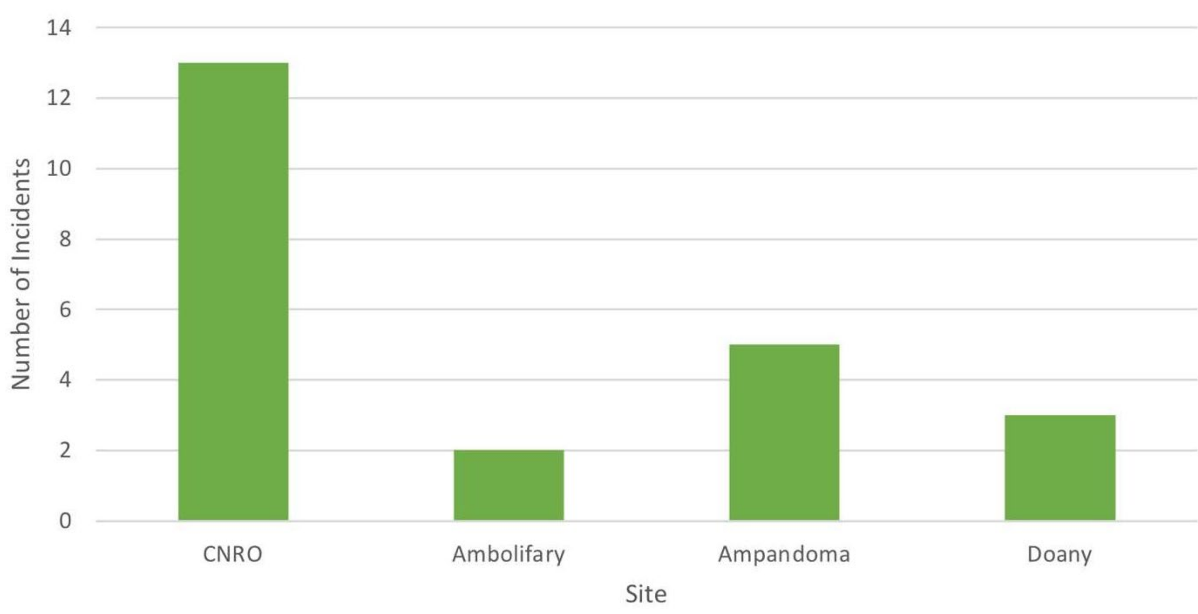

Figure 12. Incidents of soft coral colonization on hard coral by site. Area surveyed per site = 400 m^2.

Discussions

Coral Composition

Ambolifary and Nosy Komba

The coordinates of the two sites I took data from in common with Allen-Waller are almost exactly equal to her coordinates, yet depth varies in Nosy Komba since my data suggests a range from 4 to 6 meters while AllenWaller's recorded depths ranged from 1.5 to 3 meters. While estimation may play a factor in this difference, it's also possible that within the same area, Allen-Waller chose stations closer to the shore and were therefor shallower. Visibility also varied between 2015 and the time of my data collection, but turbidity and water visibility are much more flexible and changing that temporal change would likely see visibility change as well.

Inconsistent with the initial hypothesis, Porites continued to be expressed in Ambolifary more than Acropora. However, while Acropora percent composition stayed the same since 2015, Porites dropped by 3% with the introduction of Platygyra, which wasn't expressed at all between all sites in 2015 (Allen-Waller, 2015). This increase in diversity is unexpected as Ambolifary and Nosy Komba were expected to experience biodiversity loss over the last 8 years. Ambolifary had the lowest coral cover out of any of the present sites, which is consistent with Allen-Waller who found the lowest coral cover in Ambolifary as well. However, coral cover was 13% higher in my study than in 2015, indicating coral regeneration and reproductive success. Among this new growth, it is possible that Platygrya was newly introduced either naturally or from human introduction. Another possibility is that Platygyra wasn't observed in the original study out of happenstance.

Consistent with the initial hypothesis that Acropora will dominate due to biodiversity loss, the genus was expressed 18% more than in 2015. Inconsistent with my hypothesis, it wasn't the lesser represented genera that disappeared, it was the second most represented, Porites, which dropped from 35% to 16% (Allen-Waller, 2015). Porites was also found to be most susceptible to disease in 2015, suggesting that diseased corals have since died, leaving the reef with a lower composition of Porites. Nosy Komba has seen the disappearance of Montipora completely, and a slight shrinking of Galaxea, Seriatopora, and Echinopora, and the introduction of Pocillopora and a doubling in Favia (from 3% to 6%). Perhaps the most intriguing finding, Nosy Komba which had a total coral cover dwindling at around 30% now has the highest coral cover of any site in my study (60%). This refutes my initial hypothesis that coral cover would be lower than in 2015. The most likely explanation is community efforts in reef protection, as previously discussed on page 15 (MRCI, 2019). It's also possible that the decrease in tourism during the worldwide Covid-19 epidemic gave way for reef regeneration, as it did in Hawai'i after just 6 months of decreased tourism (Morimoto, 2020).

Across Other Sites

All sites outside of Lokobe on Nosy Be showed higher percent coral cover than Ambolifary, which was identified in Allen-Waller as a protected area and is adjacent to Lokobe's actual protected marine boundaries (Allen-Waller, 2015; Madagascar Protected Areas, 2023). While it's unknown if other sites in Lokobe have higher coral cover than in Ambolifary, it's clear that the unprotected sites outside Lokobe have a comparable if not higher coral cover than currently protected areas. Since my unprotected sites are incomparable with the sites studied in Lokobe in the past, further study is required in both my sites and sites across Lokobe simultaneously to confirm this conjecture (Allen-Waller, 2015).

While CNRO and Ampandoma were almost half composed of Porites, taxonomic variation was much higher in Doany, where Porites represented 35% of coral genera, Acropora and Montipora both represented 23%, and four more genera were expressed in smaller percentages. Doany and CNRO expressed seven total genera each and Ampandoma expressed eight genera, so diversity is slightly lower in those sites than in Ampandoma. Among them, Favia was expressed in all sites but Ambolifary, and Platygyra was expressed on all sites but on Nosy Komba, suggesting that these two are quite durable since they successfully live in a large variety of sites, depths, turbidities, and proximities to potential dangers. Surprisingly, no Platygyra were observed in the 2015 study, suggesting that perhaps they have been newly introduced in Nosy Be (Allen-Waller, 2015).

Bleaching

Relative to the percent of hard coral cover at each site, bleaching counts were surprisingly low. Nosy Komba had a vastly higher abundance of bleaching than any other site, but also had the highest coral cover with the highest percentage of Acropora across all sites in relation with other expressed genera. Since bleaching mostly occurs in this genus (Figure 7), in conjunction with the site's high coral cover, higher bleaching counts would be expected. Furthermore, total bleaching counts on Nosy Komba, which was the highest in both studies, has almost halved since then, indicating proper recovery. Contrary to my hypothesis, both Ambolifary and Nosy Komba displayed much lower amounts of bleaching than in 2015. Given that ocean temperatures have increased, playing a role in the death of 30% of global coral, these results are unexpected (NOAA, 2023; Hancock, WWF). One possible explanation is that local communities have decreased their disruption to reef ecosystems and have begun protecting their reefs as the government has done to Lokobe. Contrary to my hypothesis, CNRO doesn't have high bleaching counts as its proximity to human civilization and sea traffic don't seem to make hard corals more susceptible to bleaching.

Taxonomic variation in bleaching on Nosy Komba was low; bleaching counts occurred almost exclusively in Acropora, which was also the most represented genus at that site. Of the other four sites, where Porites was the most represented genus, almost equal distribution of bleaching across the two genera occurred. This representation of Acropora bleaching despite a higher composition of Porites indicates that Acropora is the most susceptible to bleaching. The data in Figure 7 support with this claim, where total incidents of coral bleaching in Acropora are over twice that of Porites.

Disease

While all sites displayed extremely low counts of disease, CNRO and Ambolifary had the least: 1 incident at each. Ambolifary had about 20 incidents of disease in 2015, mostly coming from Porites white syndrome (Allen-Waller, 2015). At the time of my study, its one incident was from Favia white syndrome. While diseases live shorter and spread faster than bleaching and coral colonization, it's surprising that disease has dropped so much in 8 years. The best explanation is that Lokobe began protecting its reefs in 2014, just before the initial study in 2015, so the conditions then would have not been very different than the reefs' conditions before its protection. During its 9 years of protection, the Malagasy government must have made efforts in eradicating disease from protected corals. Ambolifary's close proximity to protected reefs likely allows it to benefit from this eradication as well. CNRO's low disease rates cannot be explained by its proximity to Lokobe boundaries, because it's farther away and close to human habitation where corals should be more disturbed and therefore vulnerable.

Nosy Komba, which has the most incidents of disease out of all sites surveyed, has much fewer in my study than in 2015, where counts totaled in the 40s (Allen-Waller, 2015). Between the sites on Nosy Be and Nosy Komba, the most represented disease on Nosy Komba was tissue necrosis, where 31% of the island's disease was represented by Porites tissue necrosis and 25% was represented by necrosis in other genera. In 2015, Allen-Waller found Porites white syndrome to be the most abundant disease in Nosy Komba. These results make sense since white disease in Porites and Hydnophora is characterized by mass tissue necrosis (Ainsworth et al., 2007). It's likely that corals affected by white syndrome either died and were regenerated by a new colony or survived but suffered mass tissue necrosis. Cumulatively on Nosy Be, diseases varied in relatively equal distribution, but necrosis across all genera was more represented than other diseases. This suggests that across Nosy Komba and Nosy Be, tissue necrosis is the reef's most impactful problem, and since it's likely that necrosis was caused by other diseases from the past, projections for the future indicate that reef health will improve as new colonies grow in the absence of high disease counts.

Algal and Soft Coral Opportunism

Algal colonization was highest in Ampandoma (17 incidents), followed by Doany (11 incidents), which were also sites closest to sea grass ecosystems, with Ampandoma being directly adjacent and at times overlapping the sea grass environments. The proximity of Ampandoma and Doany to nearby sea grass provides a reasonable explanation for their higher density of algal assembly. Even with this explanation considered, these counts of algal colonization are by no means especially higher and dangerous, but further study is required to see if algal assembly will rise over time and threaten these reefs on a significant level.

Ambolifary had the lowest count of algal assembly (4 incidents), which could be in part attributed to the low coral cover at this site (see Figure 5). Further study into the taxonomic variation of algal colonization is required to determine if some genera are more or less prone to algal colonization, since the majority of Ambolifary is made up of Porites.

No soft coral colonization on live hard coral was observed in Nosy Komba, which is surprising considering the same site had the highest soft coral colonization out of any site in 2015, and soft corals live longer than hard corals due to their resilience to bleaching (Allen-Waller, 2015; Hawley, 2022). Ambolifary was high in soft coral colonization in 2015 (11 incidents) and is low in my study (2 incidents). The same pattern as Nosy Komba persists at this site on Nosy Be, indicating that soft coral disappearance may be linked to general oceanic conditions such as heating or acidification rather than site-specific ones such as anthropogenic regeneration or disturbance. However, it is possible that Ambolifary's proximity to freshwater output is the cause of the algae's lack of success at that sight. Similarly, further study is required to determine whether genera like Porites are more successful near freshwater outputs than other genera.

The highest count of coral colonization was measured in CNRO, the western-most reef and the closest to large human habitation. Although bleaching, disease, and algal growth was average compared to the other sites, CNRO exhibited a much higher count of soft coral colonization than any other site. One possible interpretation of this result is that since CNRO is the only reef that seems to have no anthropogenic protection — given Nosy Komba's protection by its coastal village community, Ambolifary's close proximity to Lokobe, and Ampandoma and Doany having been regenerated and protected by their local communities — CNRO is the only site to exhibit truly unprotected conditions. This caused soft coral growth to spread unregulated. Since these corals are potentially more resilient in higher temperatures than hard corals, and ocean temperatures are rising by the year, soft coral growth is expanding in unprotected reefs faster than hard corals, whose reproduction is likely hindered by the rising temperatures (NOAA, 2023; Hawley, 2022; Chandran et al., 2015). In other words, due to high ocean temperatures caused by global warming, hard coral growth is hindered without anthropogenic help, and soft corals have found an ideal breeding ground in the vulnerable hard corals and have healthier reproduction on the affected reefs. With this interpretation in mind, soft corals must also have a higher resilience to pollution and water turbidity, since both are linked to large human habitation.

Limitations, Considerations, and Further Study

In comparing my data to that of Allen-Waller, seasonality is an important factor to consider. Seasonality may play a part in why disease and bleaching counts are lowered, and since Allen-Waller's research was done in November and mine in April, disease and bleaching may be higher in Madagascar's dry season as opposed to the wet season when my study was done.

Another consideration is depth. Even shallow-water tropical corals can live in colonies as deep as 30 meters underwater (GFOE, 2023). No depths over 6 meters were observed, and the shallowness of the water could affect how bleached and vulnerable corals are, so further study including scuba diving is required to observe a wider range of depths of reef ecosystems in the area. Notwithstanding this inaccessibility to depth variability, the significantly higher depths that were studied in the present study do differ greatly from 2015, even in the two sites that were observed in both studies (Allen-Waller, 2015). As the present study suggests, slightly deeper corals may have better overall health than slightly shallower ones since depths only up to 3 meters were chosen for study in 2015, and all depths were used for observation in the present study, reaching depths of about 5 meters at times.

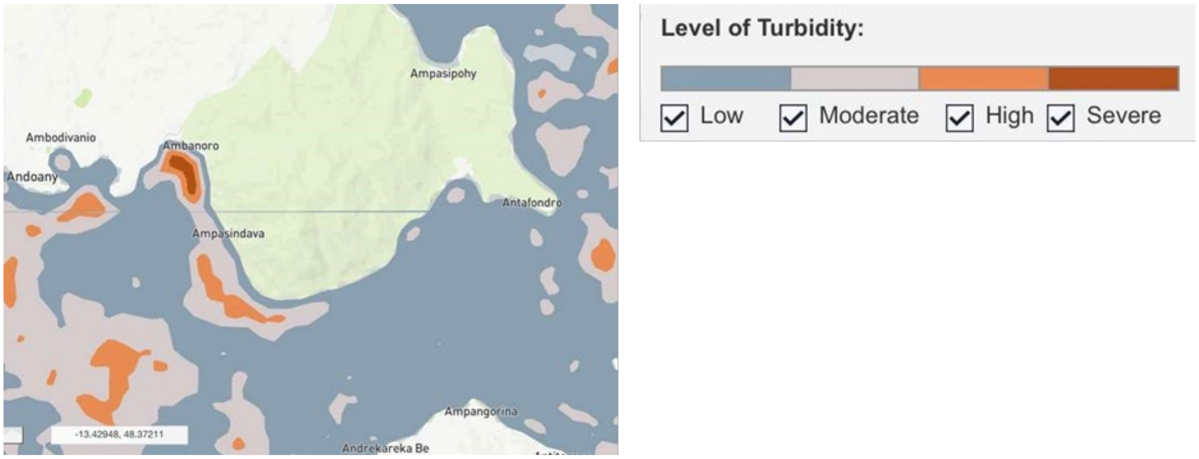

Figure 13. Water turbidity across southeast Nosy Be and northern Nosy Komba. Projection by Allen Coral Atlas, 2023.

Visibility as an assessment of turbidity isn't very effective given the Allen Coral Atlas projection and considering the visibility of each site on Table 1. The most turbid site according to the figure is Ambolifary, which also had the lowest visibility. However, Ampandoma had an equal visibility but its turbidity is low according to the figure. The low visibility at this site is due to algal and floral debris in the water from the adjacent sea grass environment. While CNRO was in a low turbidity zone, on the map it's near a moderate to high turbidity zone, so the observed visibility makes more sense. Further study into the relationship between turbidity, visibility, and coral reefs is required to assess the impacts of turbidity on overall coral health.

While a wider range of unprotected sites were studied in the present research, a study of both protected and unprotected sites at the same time is required to make better claims about the difference of coral health between unprotected and protected sites. It would also be valuable to observe these sites over the course of a year to observe seasonal changes, and over multiple years to observe annual changes as climate change worsens.

Implications

As my results suggest, the overall health of the coral reefs is relatively good to their health in 2015 and the state they were expected to be in due to climate change projections (Allen-Waller, 2015; NOAA, 2023). The likely cause of this regeneration and success is local community-based protection projects. Much like on Nosy Komba where the reef isn't government protected but claims to have become protected, Doany and Ampandoma to the east of Lokobe on Nosy Be have been said to be protected by the nearby communities (MRCI, 2019). According to CNRO's director Adouhouri Aly Bachiry, local regeneration projects have occurred on these reefs after near death, which is why health and population is generally thriving for these new reefs. The prospect of community involvement in conservation across the world is crucial in the effort for climate change mitigation, especially in third world communities where access to education and the ability to aid in conservation are scarce. Nevertheless, government involvement in the official and enforced protection of these reefs is required to better ensure their security and survival. The sites observed in this study, which are all unprotected, have higher coral cover and biodiversity than the currently protected sites within Lokobe National Park (Allen-Waller, 2015; Allen Coral Atlas, 2023). In addition, many reefs around Nosy Be and around the islands and coasts of western Madagascar should be studied and considered for official protection. Finally, anthropological research in the local communities around the sites studied would inform the extent and motive for coral protection by humans and how the relationship between these communities and their environment have changed or stayed the same over time.

Declarations

Ethical Approval

While no ethical committee reviewed this research, Data was taken respectfully to the ecosystems involved. No live corals were harmed or even touched, no outside chemicals or foreign objects were placed on the reef, and no organic or inorganic materials were taken from the reef or anywhere near the locations of the study. My methods required no samples to be taken and no tests to be run; all data was taken observationally via snorkeling.

Competing Interests Statement

The locations of chosen sites were determined ultimately by me, although CNRO's director Bachiry helped inform me about viable locations that would be accessible from CNRO's campus on a small speedboat. Funding was provided by SIT Study Abroad with no requirements or regulations on how the research would be done or where it would occur. No favors, gratuities, or other conflicts influenced the course of this research.

Funding

Funding was provided by SIT Graduate Institute – Study Abroad. No other favors or funding were accepted.

Data Availability

All data described in this paper are accessible to anyone with access to this research. All relevant links are provided in References on page 35. To contact the author of this article, I am available at jacefullertown@gmail.com .

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Appendix

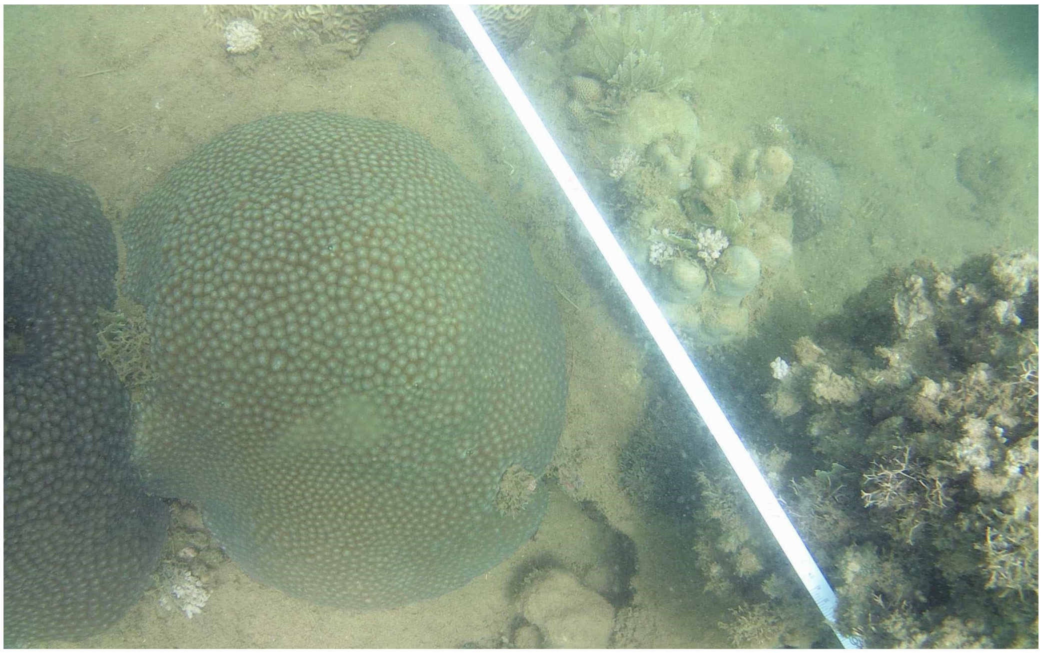

Figure 14. Favia, in massive growth form, shown next to the line of transect.

A B

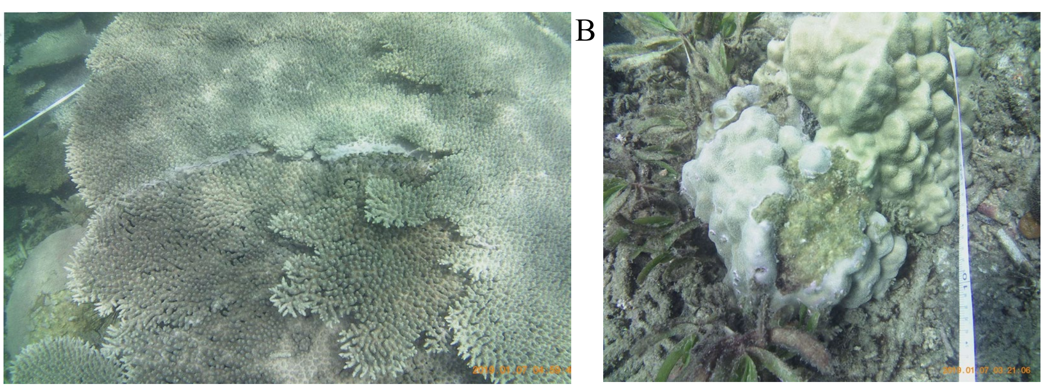

Figure 15. Corals experiencing different conditions. A: Acropora in tabular growth form with white syndrome, a white band that stretched across the colony. B: Porites in encrusting growth form with algal assembly growing out of it. On the left of the coral is sea grass and dead coral debris.