Reconstruction of Coral Reef Ecosystem Health in Lagoon Cay, Belize Using Invertebrate Assemblages in a Reef Matrix Core

Senior Research Thesis

Submitted In Partial Fulfillment for the Degree
Bachelor of Science in Earth Sciences
with Research Distinction

By

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2024

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Acknowledgements

I would like to express my sincerest appreciation to Dr. Jill Leonard-Pingel for her guidance, support, and mentorship throughout the course of this research project. Her expertise, insightful feedback, and unwavering encouragement has been instrumental in shaping the direction of this thesis. I am truly grateful for the time and effort Dr. Leonard-Pingel has dedicated to reviewing and providing constructive feedback on my various drafts of this thesis. Her commitment to academic excellence and passion for paleoecology has inspired me to strive for the highest standards in my work. Her commitment to fostering curiosity and critical thinking has been a source of inspiration, and I am thankful for the opportunities to learn and explore under her guidance. Without her due diligence, this project would not have been possible.

I would like to thank Megan O'Quin for their incredible support and assistance through this process. Megan played a pivotal role in providing valuable insights, expertise, and technical assistance that greatly contributed to the successful completion of this research. Their patience, dedication, and willingness to share their knowledge and passion have been instrumental in shaping the methodology and analysis of this study. I am grateful for the mentorship and encouragement I received from Megan. Their enthusiasm for research and commitment to academic excellence served as a constant source of inspiration. Additionally, the constructive feedback and thoughtful suggestions provided by Megan, significantly enhanced the quality of this thesis. Working together has not only expanded my understanding of the subject matter but has also fostered a collaborative and supportive research environment, and not to mention a lifelong friend. I appreciate the time and effort they invested in me, discussing ideas, troubleshooting challenges, and contributing to the overall success of this project! Megan, thank you so much!

I want to extend my deepest gratitude to James St. John, the professor who "corrupted" me into loving all things Geology. If he did not take me under his wing and share his passion for earth sciences with me, I would not be where I am today. His enthusiasm and love for teaching has inspired me in so many ways. I truly aspire to be a professor just like him and be able to portray such a passion for the earth like he has.

I would like to acknowledge The Smithsonian Museum and the University of California San Diego for providing the funding sources necessary for making this research project possible. I also want to thank The Ohio State University School of Earth Science's Friends of Orton Hall fund for their assistance with this project.

To my parents Jeff and Karen Manross, whose love for the ocean has been a constant source of wonder and curiosity in my life, thank you for instilling a passion in me for the environment and a deep appreciation for the wonders beneath the waves. Their enthusiasm for marine life has shaped my research interests and fueled my determination to explore the mysteries of the sea. To my father, your adventurous spirit, and drive for greatness have always been a guiding light. I want to express special appreciation to my mom, for her dedication to my education. Her commitment to homeschooling me not only provided a solid academic foundation but also fostered a love for learning that extended far beyond the classroom. Both of you have played pivotal roles in shaping my academic journey and inspired me to delve into the complexities of my love for the ocean. I carry your values and love with me as I embark on new challenges. Thank you both for your unconditional love and support wherever I go!

Abstract

Coral abundance is declining worldwide due to anthropogenic factors such as overfishing, agricultural advancements, and human driven climate change. While we have abundant data on reef coverage from underwater surveys completed in recent decades, there remains significant gaps in reef ecosystem data predating the 1970s. Reef matrix cores can help fill this knowledge gap by providing long-term records of reef community change prior to global-scale anthropogenic disturbance. We analyzed subfossil invertebrate assemblages preserved in lagoonal reef-matrix cores from Lagoon Cay, Belize. Bivalves, gastropods, coral, and echinoderm spines were sorted from sieve residue at 5-cm increments. Bivalves and gastropods were identified and counted. Echinoderm spines and coral were identified and weighed to obtain proportional abundance. All were identified to the lowest taxonomic level, typically to genus. Observed in this core is pre-colonial stability amongst the represented taxa. These stability patterns signal the abundance of available hard substrate (i.e., reef building corals). Herbivorous gastropods dominated the gastropod assemblage throughout the core, which is likely due to the abundance of benthic algae accessible to graze on over hard substrate. Despite its role as a keystone herbivore within Caribbean reefs, *Diadema antillarum* was not the dominant urchin anywhere in the core. Instead, *Echinometra spp.,* the dominant urchin on these reefs today*,* was the most abundant urchin in all sections. The trends in available taxa show a healthy reef in the represented time. This contrasts other Caribbean cores as well as other cores from Belize. This could be due to the core not extending far enough into the present with the most recent date being 1867. Investigating long-term changes in coral reef invertebrate communities can reveal the ecosystem-level effects of recent declines in Caribbean reef-building corals.

Introduction

Modern Coral Reef Background

Coral is a colonial animal that grows a calcareous skeleton that can form reef structures. These animals are primarily located in tropical regions around the equator because the conditions of the ecosystem are perfect for them to grow in. Reef building corals are tolerant of warm, tropical waters ranging in temperatures from 23°C - 29°C, and saline conditions ranging between 32‰ - 42‰ (NOAA, 2023). Some heartier corals, such as *Acropora hyacinthus* and *Porites lutea* can withstand temperatures up to 40°C for brief periods of time (Fitt et al., 2001; Toller et al., 2001). Corals feed on plankton as a source of food, but also have a symbiotic relationship with zooxanthellae, a photosynthetic algae, which is invited to live in the external soft tissue of the coral organism (Karako et al., 2004). These unique organisms inhabit the coral as a home and in return provide photosynthetic energy for the coral. The coral animals are sensitive to changes in their surrounding environment; especially rapid fluctuations in temperature and salinity. When the coral organism becomes too stressed due to an environmental change, it expels the zooxanthellae from its tissue. The zooxanthellae, aside from the plankton, are the main food source for coral and give them their beautiful colors. When the symbiotic algae are expelled, corals lose their color giving them a bleached look (Toller et al., 2001). This also leaves the coral in a vulnerable state making the coral more susceptible to diseases, such as white-band disease on *Acropora spp.* and yellow-band disease on *Orbicella spp.* These diseases are the two main diseases currently spreading through the Caribbean. The increase in the diseases among corals may be due to thermal stress from increases in surrounding water temperature (Van Woesik & Randall, 2017).

Anthropogenic Factors Contributing to Reef Decline

Modern Caribbean coral decline has become a prominent topic amongst scientists. Since the 1970's, scientific systematic surveys of reefs have become more regular due to the increase in SCUBA accessibility. With the increase in underwater reef surveys, scientists have determined that reef building coral has declined by about 50% (Cramer et al., 2015). However, in areas around the equator, for example Belize, up to 95% loss of reef building coral has been documented (Cramer et al., 2015; Hughes et al., 2017; McClenachan et al., 2017). Most of the more recent decline is due to anthropogenic factors such as climate change, rapid increase in unsustainable fisheries, run-off pollutants, and agricultural advancements (Cramer et al., 2015, 2020; Muraoka et al., 2022; Otaño-Cruz et al., 2019). Humans do not consider the damage of many current practices that are detrimental to benthic ecosystems. The United States military attempt to target locations for trial missile launching and landing in the middle of the oceans (i.e. Pacific and Atlantic Oceans) in order to sustain human life, although this has a negative effect on marine life (Porter et al., 2011).

Both exploded and unexploded missiles are causing damage to the environment. Additionally, in the oil and gas industry, repeating depth charges are set off in various locations every few seconds allowing these companies to better map the underground rock structures and determine oil sources. Both actions of missile fire and oil exploration disrupt and inflict rapid, unnatural death into the ecosystems (Porter et al., 2011).

The introduction of organized agriculture has been beneficial for this growing population but detrimental to natural ecosystems. Run-off correlated with agricultural advancements, such as heavy machinery, is degrading shallow reef ecosystems due to the chemicals running directly into the water. In addition to the run-off, the increase in CO_2 emissions from the equipment is adding to the global greenhouse gas. This increases atmospheric temperature which overall increases the ocean temperature and decreases sea water pH (Fitt et al., 2001). Not only is agricultural production important but fishing is as well to humans. Seafood is a main staple food in households throughout the world. Overfishing of any type of fish or animal disrupts the food chain and will collapse the ecosystem. If sharks or other apex predators are overfished, the prey animals reproduce more rapidly, overtaking and crowding the reefs. If the prey animals are minimized, the apex predators are lacking food. All scenarios disrupt the surrounding ecosystems substantially.

Belize's Historical Background

Indigenous Maya lived on the island of Belize until the Spanish colonized. The first European contact was in the early mid 1500's and that is when the Maya populations started to decline. The first English settlements were built in the late 1600's (Muraoka et al., 2022). Then in the mid 16th century, Spain granted Britain logging rights for the mahogany groves, and by the mid the 17th century, the British had expanded by establishing settlement (Church et al., 2019). By the 1880's they were building banana plantations in the Stann Creek district (Church et al., 2019; Moberg, 1996). Tourism began to fuel their economy in the 1970's and grew substantially after their independence in 1981 (Medina, 1998). Belize has many beautiful natural attractions that are worth traveling to see such as wetlands, beaches, mangroves, and coastal lagoons. This country is home to the largest barrier reef in the Western Hemisphere, the Mesoamerican Reef, attracting a large amount of tourism, contributing about 30% to the nation's domestic product (Gibson et al., 1998). This increase

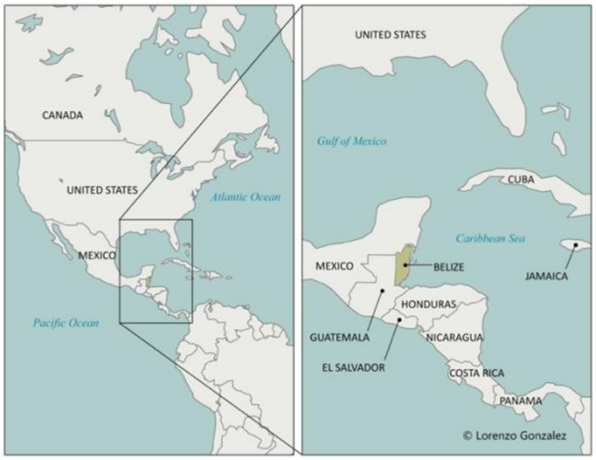

Figure 1 - Location of Belize in Central America.

in tourism is very beneficial for economies but not always great for the surrounding natural ecosystems. With an increase of income also comes an increase in sunscreen, food demand, and traffic in and on the oceans. Marine tourism, however, is extremely important for conservation of shallow reef ecosystems, when regulated properly. It provides exposure to certain species or ecosystems tourists might not have near their home, and it can spark an interest in its protection. This is why national parks and marine parks are so helpful in maintaining and growing an area that may need rehabilitation, or simply just maintenance (Claudino-Sales, 2019). In 1983, Belize has implemented seven marine areas of protection. Since then, in 1996, all seven were transformed into national parks or marine reserves and continue to push efforts in protecting these areas (Claudino-Sales, 2019). Within these natural ecosystems, biodiversity has been increasing and thriving. It has been recorded that there are over 500 species of fish, more than 350 molluscs, and 126 coral types which account for 90% of the Caribbean coral biodiversity (Claudino-Sales, 2019). Although this biodiversity is flourishing, reef ecosystems are still declining, including the main framework reef builders, by 44% (García, 2022).

The Role of Conservation Paleobiology in Studying Reef Degradation

Conservation paleobiology is a field that has developed more recently and is becoming more crucial to studying modern ecosystem decline (Dietl et al., 2015). Since most of the global reef monitoring began in the 1970s, there is a lack of data predating this time. Information about coral reef decline previous to 1970 could help scientists better understand the history and mechanisms of decline. The integration of subfossil data with modern data can be used to construct a more comprehensive understanding of the long-term trajectory of coral reefs. Having an accurate baseline is a fundamental component of researching paleobiology in reefs for several reasons: assisting in providing a historical context for understanding the local ecosystem dynamics, detecting natural biota fluctuations, assessing human impacts, guiding restoration efforts, informing conservation strategies, and ensuring the reproducibility of scientific studies. Parrotfish teeth are well preserved in reef matrix cores and have become a great indicator of reef ecosystem changes directly correlating with abundance or lack of hard substrate (i.e. corals) (Cramer et al., 2015, 2020, 2021). Throughout the Caribbean, coral cover has had a shift from species to species (i.e. *Acropora spp.* to *Porites spp.*) and also from hard coral cover to macro algae (Precht et al., 2020). Even before the increase in reef surveys during the 1970's, the reef ecosystem has been degrading for a long time. This decline can be tracked back to the early 18th century and largely stems from an increase in colonization of the Caribbean islands and advancements of agricultural cultivation (Cramer et al., 2021). As evident in cores from Panama and Belize, parrotfish abundance is much lower than their pre-European colonization peaks due to an increase in fishing (Muraoka et al., 2022).

Invertebrates as Indicators of Environmental Change

The analysis of reef matrix cores provides long-term records of reef community change prior to global-scale anthropogenic disturbance. Much of the research conducted regarding coral reef decline is centered around reef fish, echinoderms, algae, and coral. Groups such as molluscs, specifically bivalves and gastropods, are understudied relating to coral reef decline. When analyzing reef degradation, both molluscs and echinoderms will help provide a better understanding of the conditions spanning the represented time because they are easily preserved and abundant throughout sediment cores. In this study, we focus on epifaunal bivalves, herbivorous gastropods, and echinoderm death assemblages. Each of these groups provide a very specific insight into the surrounding reef environment and the health of the community. Epifaunal bivalves show the accessibility to hard substrate (i.e. coral versus sediment) due to their attachment types whether they are infaunal or epifaunal. Herbivorous gastropods may indicate the presence/abundance of seagrass due to their diet being strictly sea grass and algae in their environment. *Diadema spp.* are a keystone herbivore so an abundance of them would lead to an insight on the environment with and increased sea grass presence (Cramer et al., 2020). These three groups will provide us with strong indicators of the surrounding environment throughout the core sample.

Leading Hypotheses

Considering the anthropogenic impacts throughout time, we are expecting to see the following reflected in our data…

- A decrease in abundance of *Acropora spp.* corals due to the reef degradation that has been documented.
- Shifts in dominant feeding type of molluscs. In the bivalve molluscs, deposit feeders should be dominant, specifically chemosymbiotic feeders. In the gastropod molluscs, we expect to see an increase in herbivorous gastropods due to a decrease in hard substrate corals.
- An increase in infaunal bivalves accompanied with a decrease in epifaunal bivalves.
- An abundance of *Diadema spp.* spines in the assemblage because of their role as a keystone herbivore. Recently, they had a large mortality event, so we anticipate a decrease in *Diadema spp.*, closer to the top of the core.

Methods

The sediment core presented here was collected from a near reef rubble zone in Lagoon Cay, Belize. The Lagoon core, is one of three collected. At the time of coring, Elbow, Bakers, and Lagoon Cay cores are the three cores obtained. Core collection was accomplished using SCUBA as well as a combination of push-coring and vibra-coring techniques.

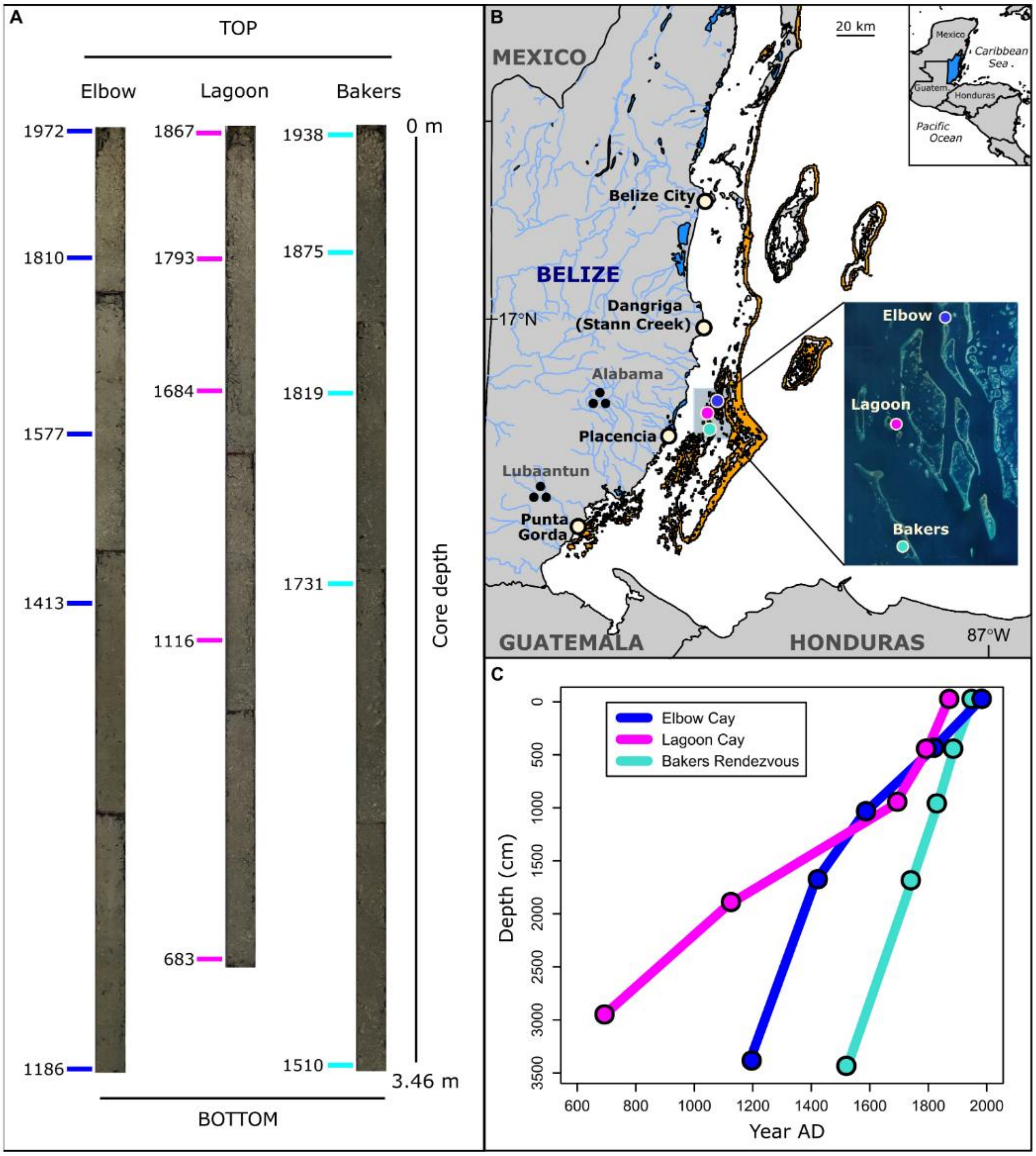

Figure 2 - Highlighted location in magenta that the core was extracted off the coast of Belize (Muraoka et al., 2022).

Figure 3 - Lagoon core >2mm sections being unboxed that have not yet been picked.

Figure 4 - Picking process includes the initial separation of echinoderms, bivalves, and gastropods.

Figure 5 - Picking through the >2mm section of the Lagoon core using the dissecting microscope and tweezers.

Figure 6 - Arene spp. identified and sorted from a >2mm core section, ready to be labeled and set aside.

The 3.5m core was sectioned into 5 cm sections and sieved, with >2 mm residue reserved for taxonomic analysis (Figure 3). Invertebrate sub-fossil material was picked from the sieve residue, quantified, and identified (Figure 4 and 5). Each individual was identified to the lowest taxonomic rank possible using Keen (1971) and Redfern (2003); taxonomic groups were assigned to functional groups (e.g. trophic group and substrate relationship) using the NMITA database (Todd 2003) (Figure 4). Quantitative data was generated by counting bivalve and gastropod individuals, using the protocol of Gilinsky and Bennington (1994), and weighing coral and echinoderm fragments. Uranium-Thorium dates were obtained for five coral fragments, one at each 0.5m through the core and one additional at the bottom. These were used to interpolate the rest of the dates in order to provide us with a timeline for the core in calendar years.

The proportional abundance of functional groups and select genera were analyzed to explore change in the community composition throughout the time. The >2mm fractions were carefully picked through using a dissecting microscope and tweezers (Figure 5). The bivalves, gastropods, coral fragments, and echinoderm spines were picked from the core section. To include each bivalve individual, an intact umbo and hinge line needed to be present. An apex or aperture must be intact as well, to count as a gastropod individual. Both processes follow the protocol of Gilinsky and Bennington (1994). Once finalized, the excess algal material and unidentifiable material was returned to the original container. The grouped skeletal material was identified (as described above) and labeled, then separated into their own container (Figure 6).

Results

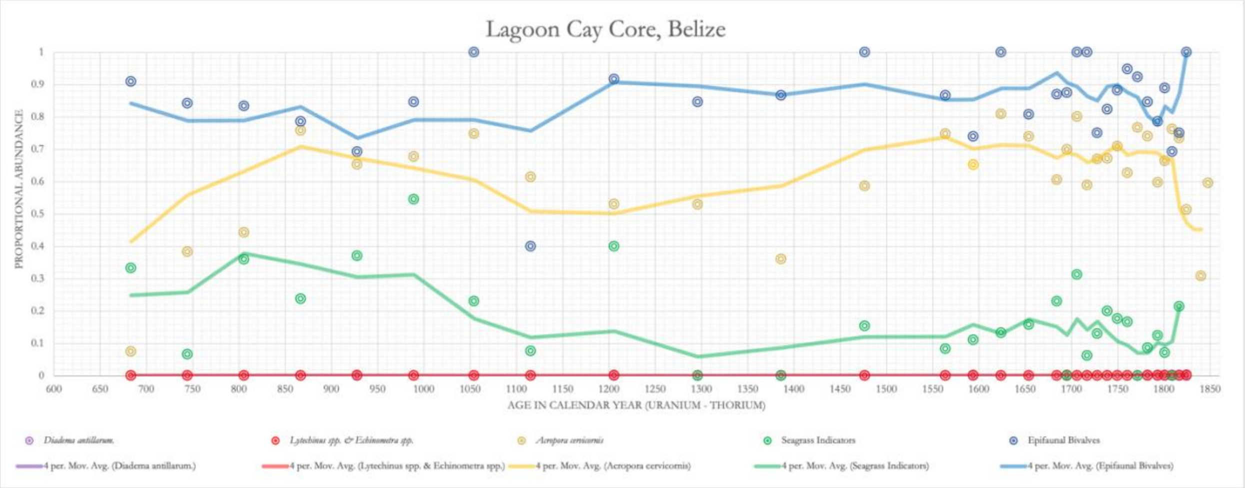

Figure 7 - All taxa graphed together. Plotted on the X-axis is the age in calendar years that spans the core, determined by Uranium - Thorium dating. Plotted on the Y-axis is the proportional abundance. The solid lines are trend lines showing a moving average of 4 points.

This graph is showing stability throughout the entirety of the core, in all sections that are plotted. The *Diadema spp*. data is hidden behind the *Lytechinus spp*. & *Echinometra spp*. line.

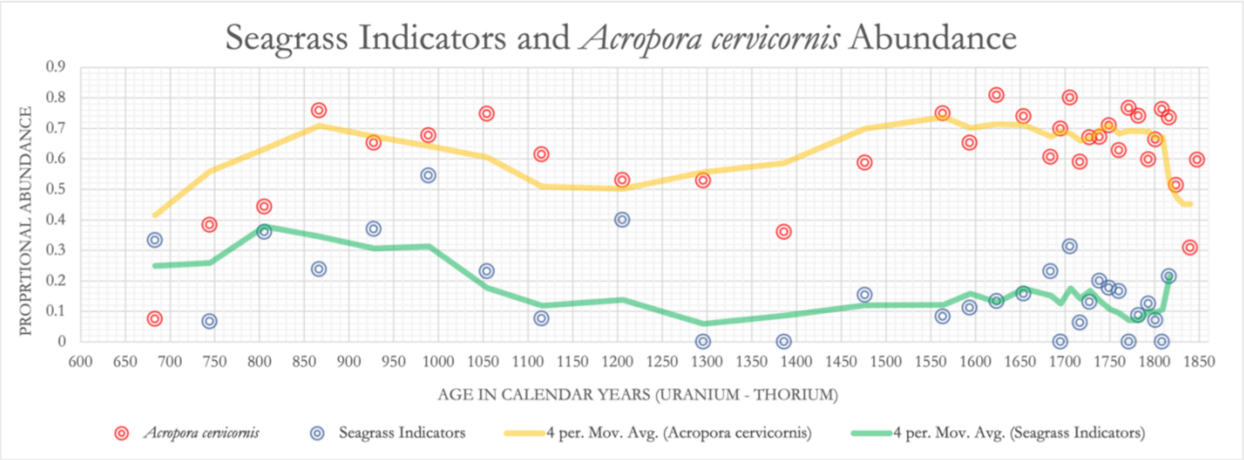

Figure 8 - Proportional abundance of seagrass indicators (herbivorous gastropods) and Acropora cervicornis throughout the core. Plotted on the X-axis is the age in calendar years that spans the core, determined by Uranium - Thorium dating. Plotted on the Y-axis is the proportional abundance. The solid green and yellow lines are trend lines showing a moving average of 4 points.

The sea grass indicators and *Acropora cervicornis* track together until the year 1200. After this, they invert and do not track together. Throughout the majority of the core, *Acropora cervicornis* is showing relative stability. Although, the last 50-70 years represented in the core shows a rapid deterioration of *Acropora cervicornis* which is met by the increase of seagrass indicators.

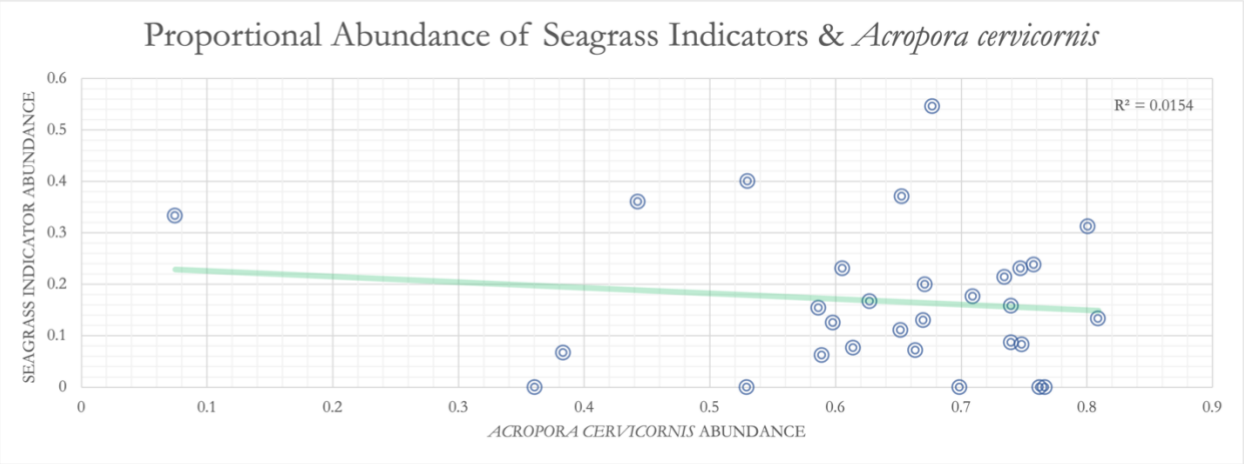

Figure 9 - Proportional abundance of Acropora cervicornis's relationship with seagrass indicators throughout the entirety of the core. Plotted on the X-axis is the Acropora cervicornis proportional abundance. Plotted on the Y-axis is the seagrass indicator proportional abundance. The green line is a linear trendline showing that $R^2 = 0.0154$.

The R^2 value is 0.0154 and we are seeing a low value due to the potential outlier points on the graph, throwing off the smoothed average. Although it generally appears, the higher proportions of *Acropora cervicornis*, correlates the lower proportions of seagrass indicators present.

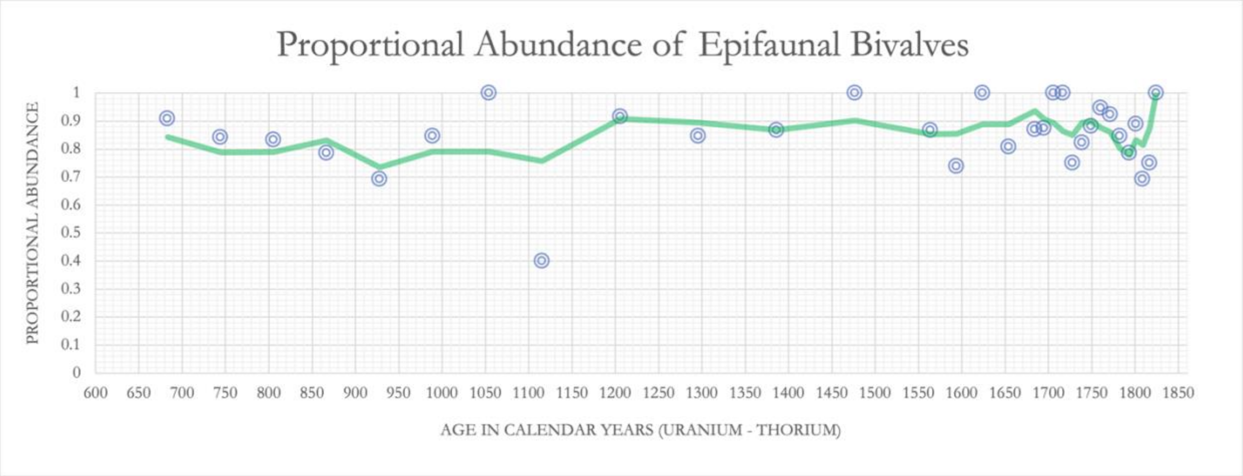

Figure 10 - Proportional abundance of epifaunal bivalves throughout the core. Plotted on the X-axis is the age in calendar years that spans the core, determined by Uranium - Thorium dating. Plotted on the Y-axis is the proportional abundance. The solid green line is a trend line showing a moving average of 4 points.

The epifaunal bivalves are stable throughout the entire core.

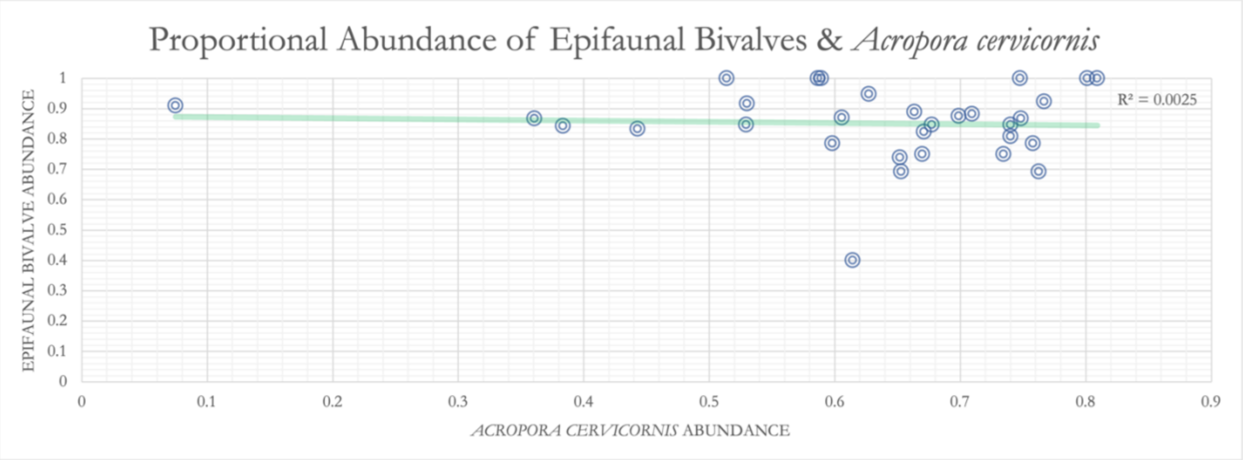

Figure 11 - Proportional abundance of Acropora cervicornis's relationship with epifaunal bivalves throughout the entirety of the core. Plotted on the X-axis is the Acropora cervicornis proportional abundance. Plotted on the Y-axis is the epifaunal bivalve proportional abundance. The green line is a linear trendline showing that $R^2 = 0.0025$.

The R^2 value is 0.0025 and we are seeing such a low value due to the potential outlier points on the graph, throwing off the smoothed average. Although it appears that the higher proportions of *Acropora cervicornis* correlates with the higher proportions of epifaunal bivalves present.

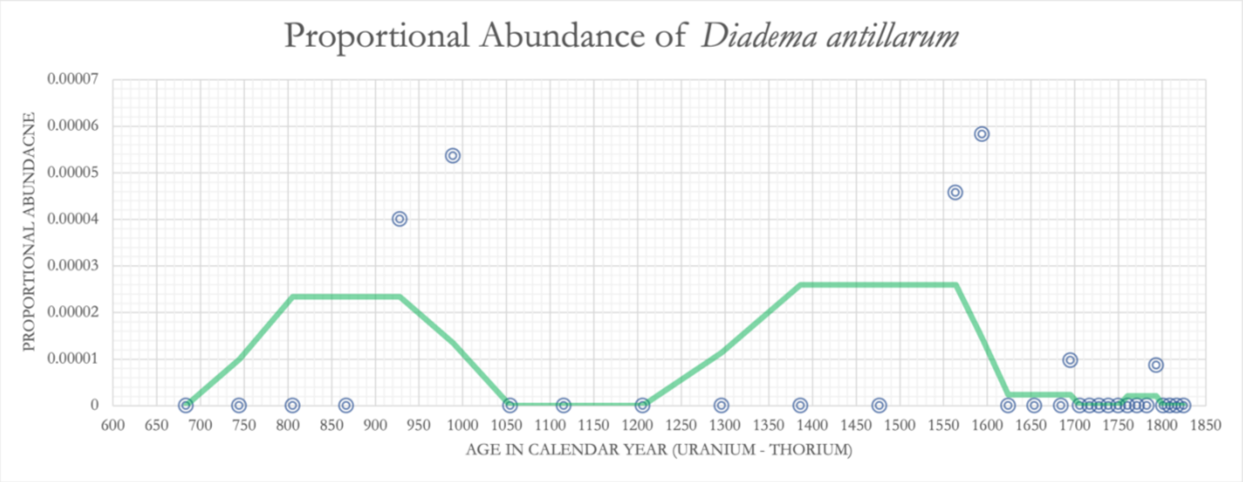

Figure 12 - Proportional abundance of Diadema antillarum throughout the core. Plotted on the X-axis is the age in calendar years that spans the core, determined by Uranium - Thorium dating. Plotted on the Y-axis is the proportional abundance. The solid green line is a trend line showing a moving average of 4 points.

Throughout most of the core, *Diadema spp.* was not present. Only a few places we found a small portion of a *Diadema spp.* spine, never an intact spine.

Discussion

This lagoonal core sample extends from the year 683 to 1867. There is no available data from the past 150 years, so it is difficult to tell what trends would continue throughout the height of the Industrial Revolution and into the present.

Acropora cervicornis

The relative stability indicates a healthy reef with higher total coral cover, averaging 60%. Other analyses throughout the Caribbean, such as Panama, have shown a deterioration of *Acropora cervicornis* a century earlier because of the land use changes (Cramer et al., 2015; Precht et al., 2020). Therefore, we did not expect to see this much stability of *A. cervicornis* in this core. Starting at the year 1200, we saw a decrease in *Acropora cervicornis* when there was an increase of seagrass indicators. This is what we want to see since they do not normally inhabit the same ecosystem. The decline at the top of the core could represent early coral degradation due to various anthropogenic factors such as increased agricultural implementation. This stability is great to see because it helps other research throughout the Caribbean determine baseline data for coral reefs and see what a reef would behave like before anthropogenic factors disrupt it.

Herbivorous Gastropods

From the years 700-1200 we see a relationship of similarity between *A. cervicornis* and the seagrass indicators tracking together, but it is not what we would expect. The higher the proportion of sea grass indicators should equate to a decrease in coral since seagrass and *A. cervicornis* are not usually inhabiting the same area. Seagrass indicators are remaining stable and low, between 1200-1750 indicating ample coral cover, this is what we would expect to see. Presence of abundant herbivorous gastropods indicates ample algae in the reef ecosystem. The fluctuations in gastropod seagrass indicators are likely showing a change in patch reef margins fluctuation from hard coral substrate to algal sea grass beds. The increase at the top of the core, paired with a decline of *A. cervicornis*, can foreshadow replacement of *A. cervicornis* with sea grass. The overall gradual decrease in sea grass indicators may be due to higher coral rubble cover, rather than live healthy coral.

Epifaunal Bivalves

The epifaunal bivalves are stable throughout the core, showing an abundance of hard substrate including high coral cover. Observing a low R^2 value of 0.0025 (Figure 11) might suggest we were incorrect about the correlation of *Acropora cervicornis* and epifaunal bivalves. However, as seen below, (Figure 13) a modern day *Dendostrea spp.* attached itself to a mooring rope line, not *Acropora cervicornis*. The low R^2 value of 0.0025, leads us to think that either the outlying data points may have thrown off the average, or that epifaunal bivalves may not need *Acropora cervicornis*, but instead, are attaching themselves to different types of hard substrate (i.e. reef rock, other hard corals, or dead corals). Additionally, all coral fragments were weighed and identified but only bivalves with an umbo and hinge line were counted and identified leading to a possible undercount in bivlaves.

Figure 13 - Modern day lower valve from Dendostrea spp. attached to a mooring line in the Exuma Bahamas.

Since the majority of bivalves represented in this core are suspension feeders, this indicates a coarser sediment (i.e. sand-sized grains) in the surrounding environment and low sediment suspension and organic material in the water column. The lack of chemosymbiotic feeders represents ample oxygen levels throughout the core exhibiting no anoxic, or hypoxic, conditions (Cramer et al., 2020; Leonard-Pingel et al., 2012).

Diadema spp. **and** ***Echinometra spp.***

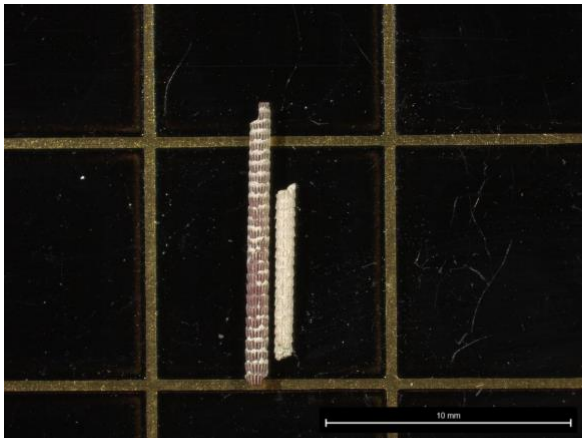

Figure 14 - Diadema antillarum spines.

Figure 15 - Echinometra spp. spines.

Diadema spp. is thought of as a keystone herbivore which grazes on algae and seagrass. Throughout the Caribbean, *Diadema spp.* flourished until 1983-1984 when there was a large mortality event and their numbers dropped roughly 93%. Since then, this urchin has made a slight comeback and began populating the modern reefs, although, there was another mortality event in 2020 (Lessios, 2016). Throughout the core though, *Diadema spp.* spines were almost nonexistent. This is the opposite of what we expected to see given their high numbers during the time represented in this core. Instead, the dominant urchin throughout the core is *Echinometra spp.* There are different physical attributes between these two species of urchins. *Echinometra spp.*, which is substantially more robust, having thicker and stronger spines (Figure 15), while *Diadema spp.* has smaller, more fragile spines, and presents scale like features (Figure 14). This can indicate a preservation bias in the area. This finding does not mean *Diadema antillarum* was not present, it just aids in showing a potential taphonomic bias.

Conclusion

The analysis of reef matrix cores provides long-term records of reef community change. This core specifically is giving us insight on the reef ecosystem prior to global-scale anthropogenic disturbance. Most of this core represents a stable, healthy reef ecosystem with high coral cover, a high proportion of *A. cervicornis*, and coarse sediment grains. The bottom of the core that represents the years 700-900, possibly indicates that the patch reef at this location in Lagoon Cay was not yet established. This would explain why we see very peculiar data at the beginning of the core in each section of data, for example, *A. cervicornis* and seagrass indicators tracking together, and a decline in epifaunal bivalves even though there is an increase in *A. cervicornis*.

Belize is different from most of the other Caribbean countries. Panama for example, was seeing reef decline as early as the 18th century, whereas Belize starts to see decline at the end of the 19th century (Cramer et al., 2015). This delayed decrease may be due to the lack of plantations on the island in earlier years. Belize's banana plantations were not established until about 1880 (Moberg, 1996). Once the Stann Creek banana plantations were established, massive land clearing occurred and that is one of the leading causes of rapid decline in Belizean reef ecosystems (Moberg, 1996). At the locality of Bakers Rendezvous and Elbow Cay, also in Belize, the cores do not show decline until the middle 20th century, but they are also both further from shore than lagoon is (Figure 2). They are located a short distance from the Lagoon Cay site but are farther offshore. Even a small difference in distance from land can decrease the influence on reefs from land-use related anthropogenic factors. The two other cores are further from shore which can create a lag in data. Since this core represents a healthy, undisturbed location, it could be used as baseline for future research on the Caribbean. Having a strong baseline is very important for the background of data sets because it gives researchers a starting point to then interpret the change.

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