The Potential of Southeast Florida’s Coral Reef Tract to Enhance Climate Resilience of Ecosystems and Communities

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This Master’s Project

The Potential of Southeast Florida’s Coral Reef Tract to Enhance Climate Resilience of Ecosystems and Communities

By

Michaella Sena

is submitted in partial fulfillment of the requirements for the degree of:

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In
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Abstract

Increasing anthropogenic greenhouse gas emissions have led to more heat being trapped in the atmosphere, raising our overall global temperature. The hottest recorded sea surface temperatures in Southeast Florida occurred in 2023 causing extreme coral bleaching and high mortality in part of the Florida Reef Tract (FRT). Coral reefs play a vital role in protecting coastal communities from storm surge and sea level rise, reducing wave energy by up to 97% across whole reefs. However, with increasing ocean acidity and thermal stress from climate change, coral ecosystems are struggling to maintain their structural complexity and overall health, much less provide substantial protection to human communities. Through a literature synthesis, environmental assessment, environmental justice analysis, and an analysis of risk management strategies, I assess the FRT’s potential to reduce flood risk from storm surge and sea level rise. This paper examines how the FRT can enhance climate resilience for both marine ecosystems and communities in Southeast Florida amidst climate change. My analyses find that coral reefs have significant wave attenuation potential only if structural complexity and carbonate accretion are high. I also find that coral reefs can reduce climate injustices in disadvantaged communities by reducing flooding from rising seas and greater storm surge. However, policies are needed to avoid climate gentrification in protected neighborhoods. I conclude that the five biggest impacts and threats to the FRT are climate change, loss of coral biodiversity, coral disease, pollution, and direct human activities such as dredging and fish trapping. Swift climate action and stringent policy are necessary to protect and sustain the benefits provided by the FRT. This includes quickly reducing greenhouse gas emissions to net zero, increasing restoration efforts, updating local sewage infrastructure to reduce pollution runoff, and implementing legislation that further promotes the protection of coral reefs.
Motivation

Coral reefs are a delicate ecosystem that provide various benefits to coastal communities and the surrounding environment. Growing up in Miami and seeing firsthand the impacts of global warming on the Florida Reef Tract (FRT) and the challenges many locals face amidst climate change has motivated me to assess how the FRT can enhance climate resilience for these communities. The FRT supports an abundance of life while also reducing impacts on local infrastructure from storm surge and sea level rise. Yet, this tropical coral reef is being severely threatened from increasing climate impacts and needs action to happen soon if we want to restore and protect this vital and dynamic ecosystem.

1. Introduction

1.1. Overview of Coral Reefs & Climate Change

While coral reefs cover less than one percent of our ocean, they support nearly 25 percent of all ocean species (NOAA 2022). This ecosystem is a vital part of our planet for myriad of reasons such as reducing shoreline erosion from storms, contributing to jobs for many coastal communities, providing food and medical resources, creating recreational spaces, and adding to our world’s economy (NOAA 2019). However, rapid increases in greenhouse gas (GHG) emissions from anthropogenic activities have altered our oceans in a way not seen for millions of years. The increased amount of carbon dioxide (CO\(_2\)) in our atmosphere is not only raising global temperatures on land and sea, but our oceans have already absorbed one third of all human produced CO\(_2\) leading to ocean acidification. Ocean acidification is particularly damaging to corals as they lack sufficient carbonate under lower pH conditions to build and grow successfully (Mollica et al. 2018). These system shifts may trigger irreversible ecological changes while causing a variety of problems including altered food webs and species distribution, a decrease in ocean productivity and reef forming species, and increasing coral diseases (Hoegh-Guldberg & Bruno 2010).
1.2. Types of Reefs & Their Composition

There are three major types of coral reefs including atolls, fringing reefs, and barrier reefs, though many other variations exist. The Florida Reef Tract (FRT) is unique in that it is made up of a cluster of different reefs making the overall structure most like a barrier reef, but it sits closer to the shoreline without the traditional inshore lagoon. It is more appropriately referred to as a bank-barrier reef and while slightly different (Florida Department of Environmental Protection n.d.a), it is still considered the third largest barrier reef globally (EPA 2024a).

Stony corals play a crucial role in the FRT system as they support the foundation of the reef (Toth et al. 2023). Stony corals are comprised of living polyps that take in calcium from the ocean and solidify as calcium carbonate (CaCO₃) to create their structure. The polyps host zooxanthellae (algae) that provide the coral with enough sustenance as they go through the photosynthesis process. These reef-building corals must exist in either tropical or sub-tropical regions in shallow waters to have sufficient sunlight for growth (EPA 2017). Stony corals typically drive reef accretion (Morris et al. 2022) and carbonate budget assessments can provide further insight into the accretion rates (Toth et al. 2023). A healthy reef will have a balance between calcification and erosion through physical and biological processes with an overall net positive growth. The FRT however is currently in a steep decline due to various stressors (Morris et al. 2022).

Three stony coral types, *Acropora palmata*, *Acropora cervicornis*, and *Orbicella* spp. were the predominant species along the FRT comprising almost 90% of the reef complexity. These corals were the dominant species for hundreds of thousands of years however rapid climate change has shifted assemblages along the FRT to more stress tolerant or “weedy” corals. These weedy corals are able to reproduce quickly, but their ability to maintain reef functions is limited (Toth et al. 2019). With stony coral degradation from disease and bleaching, the reefs have become unbalanced with calcification rates unable to keep up with erosion (Morris et al. 2022).
1.3. Benefits of Coral Reefs

Coral reefs are important in reducing wave energy and height to protect coastal infrastructure. Reefs also provide jobs in fishing and tourism and create a space for various recreational activities. The FRT has an economic valuation of over $8.5 billion USD (Morris et al. 2022) and provides 81,300 jobs (The Nature Conservancy 2018). However, if reef height is reduced by 1-m, then an additional 20 km² of Florida would be included in the 100-year floodplain putting more than 24,000 people and $2.9 billion at risk (Storlazzi et al. 2019).

Humans have traditionally accomplished shoreline protection through the use of breakwater construction such as seawalls. However, coral reefs have proven to reduce a slightly greater percentage of wave height to that of breakwaters, and coral restoration (utilizing artificial reefs) has been found to be more cost effective as a solution. Average wave height reduction from coral reefs is 51-74% versus breakwater construction of 30-70%. Additionally, median project costs for coral reef restoration and breakwater construction are $1,290 m⁻¹ USD and $19,791 m⁻¹ USD respectively (Ferrario et al. 2014).

1.4. The Florida Reef Tract

The FRT stretches approximately 350 miles from the northern point in Stuart running south to the Dry Tortugas seen in figure 1 (The Nature Conservancy 2018). The FRT has been declining in health over the past 40 years (EPA 2024a), but given coral reefs help protect coastlines from rising seas and storm surge (Toth et al. 2023) there has been greater emphasis on the protection and restoration of the FRT from various stakeholders (EPA 2024a). Florida’s coral reef is in a precarious situation not just from climate impacts, but also widespread coral disease, pollution, runoff, and human activities such as dredging (Carlson et al. 2022, EPA 2024a). These compounding effects and emphasis on protecting the FRT will serve as the overarching purpose of this study.
2. Background

The term greenhouse effect has been used to describe how gases such as carbon dioxide, methane, ozone, and others, trap heat in our atmosphere. CO$_2$ plays a significant role in balancing our Earth’s atmosphere – if there was none, the surface temperature of Earth would drop drastically. The natural greenhouse gases are what have created such a unique condition for life to exist (NASA n.d.). However, since the start of the industrial era in the 18$^{th}$ century, anthropogenic emissions, particularly carbon dioxide (CO$_2$), has been rising exponentially. There is now 150% the amount of CO$_2$ in our atmosphere than there was in 1750. Over the course of hundreds of millennia CO$_2$ concentrations haven’t surpassed 300 parts per million (ppm), but as of 1911 Earth broke that threshold and is now above 400 ppm (NASA 2023). This increase in CO$_2$ has started to alter our Earth’s equilibrium with more heat being trapped raising our global average temperature (NASA n.d.).
Our planet’s temperature has increased by ~1.1 degree Celsius with the highest recorded temperatures occurring over the past decade (NASA 2022). Global surface temperatures have increased faster in the past 50 years than any period over the past 2000 years. This has triggered a variety of climatic challenges on nature and people – particularly vulnerable communities who often contribute least to climate change. Struggles endured range from extreme heat and drought to displacement of both humans and animals fleeing homes and habitats that are no longer safe or inhabitable due to global warming (IPCC 2023b).

Our oceans have absorbed approximately 30% of all anthropogenic CO₂ (NOAA 2020) which has caused the ocean’s pH level to lower thus becoming more acidic (Doney et al. 2009). This process is what is now commonly referred to as ocean acidification (NOAA 2024) and occurs as the CO₂ and water together form carbonic acid that then dissociates into hydrogen (H⁺) and bicarbonate ions. Greater numbers of hydrogen now exist due to these acidifying conditions leaving the existing carbonate ions to bond to the H⁺. However, organisms that rely on carbonate to form their shells (such as corals) are being left with insufficient amounts to utilize and leaves them vulnerable to various stressors (NOAA 2020).

Research has shown over the past century that our ocean pH has dropped from 8.2 to 8.1 (on a logarithmic scale), translating to about a 30% rise in acidity (Webb 2021). Models predict if emissions continue at their current rate, then by the end of this century the ocean’s pH levels may reach ~7.8 – levels not seen since the middle Miocene where temperatures were warmer, and a large extinction was taking place (NOAA 2020). From 2009-2019, 14% of coral reefs had already disappeared. Under projections from the Intergovernmental Panel on Climate Change (IPCC), reefs will decline by 70-90% if global temperatures rise 1.5 degrees C and decline over 99% at an increase of 2 degrees C. This is highly concerning as the planet has already warmed by approximately 1.1 degrees C (Colbert 2023).
Another concern around our oceans is that of sea level rise (SLR). While SLR can happen naturally, the rate at which it is currently rising suggests there to be other factors contributing to its increase. Anthropogenic emissions have warmed the climate triggering an increase in glacial and ice melt, and thermal expansion (Cazenave & Cozannet 2014). Thermal expansion is caused by the warming of water molecules that increase their kinetic energy making them faster and more spread out, therefore increasing the water mass (Webb 2021). Over the past twentieth century earth’s SLR has increased more rapidly than the previous three millennia. From 1901-2018 thermal expansion has contributed 38% and glacier loss 41% to our global mean sea level (GMSL). SLR is experienced differently across the globe with some areas seeing higher levels than others (Fox-Kemper et al. 2021). Coastal erosion and shifts in shorelines are becoming more common and by the end of the twenty-first century SLR is expected to impact nearly all coastlines (Cazenave & Cozannet 2014). The Florida Keys has already seen nearly 4 inches of SLR from 2007-2017 and is predicted to see an additional 10-21 inches of SLR over the next decade and a half (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact) 2020).

Stronger storms are impacting many coastal cities as they increase storm surge which in addition to SLR puts many communities at an increased flood risk (Rahmstorf 2017). While the winds and rain of many of these storms can be problematic for coastal communities it is often the storm surge that causes most damage and mortality. Storm surge is caused by water being pulled toward the eye (center) of the storm creating greater pressure and a sudden form of sea level rise that floods coastal lands (Webb 2021). Models show with global warming comes an intensification of tropical cyclones (Bhatia et al. 2022). Cyclones (and hurricanes) form over warm tropical waters as the heat helps them form and build (Webb 2021). One study by Mei et al. 2013 found warming and cyclone intensity to correlate suggesting warm waters create cyclones and the cyclone itself warms the water creating a positive feedback loop. With coral reefs ability to attenuate wave height and energy (Ferrario et al. 2014), their role in creating coastal resiliency against intensifying storm surge and flood events is significant. However, few
quantitative analyses have been performed to understand the capacity reefs will have for coastal protection under projected climate conditions (Carlot et al. 2023).

3. Purpose, Objective, & Research Questions

3.1. Purpose & Objective
The capacity of the FRT to reduce flooding and promote coral diversity is dwindling. The purpose of this study is to determine actions needed to restore and protect the FRT to maintain its ecosystem functions. The objective is to understand the significance coral reefs play as a climate adaptation tool for Southeast Florida through various methodologies. By understanding the benefits coral reefs provide for coastal communities can help promote greater stakeholder involvement and ideally increase awareness, advocacy, and action.

3.2. Research Questions
The overarching question this paper is looking to answer is: How can coral reefs enhance climate resilience of ecosystems and communities in Southeast Florida? To answer this, I will be looking closer at the following questions:

- Sub-Question 1: How do coral reefs reduce flood risk from sea level rise and storm surge for coastal cities?
  - Objective: To provide context for the subsequent sub-questions – highlight the existing research on wave attenuation rates and coral complexity of coral reefs in order to provide coastal protection.
  - Method: Synthesis

- Sub-Question 2: What is the status of the Florida Reef Tract?
  - Objective: Determine current impacts and future risks on coral reef health in Southeast Florida to guide actions for reef management.
  - Method: Environmental Assessment
4. **How Coral Reefs Reduce Coastal Flood Risks from Sea Level Rise (SLR) & Storm Surge**

4.1. **Overview**

Chapter 4 answers research question 1: How do coral reefs reduce flood risk from sea level rise and storm surge for coastal cities? Here I contextualize the significance of coral reefs for coastal communities. Through a literature synthesis I explain the dynamics of reef systems, their benefits, and their role as a natural buffer system against SLR and storm surge. The data and research discussed in this section is pertinent to understand the subsequent chapters and overall outcome of the paper.

4.2. **Literature Review**

40% of the global population lives within 100km of a coast (Field et al. 2009), and with coastal communities rapidly developing (Ferrario et al. 2014), this percentage is projected to rise (Field et al. 2009). The tropical coasts lined by coral reefs around the world help protect over 500
million people (Carlot et al. 2023) providing storm and flood protection as well as economic support (NOAA 2018b). However, climate change is increasing the rate of SLR and the frequency of storms and flood events, all of which puts increasing risks to coastal communities (Oppenheimer et al. 2019).

In the U.S. over a 128 million people reside in a coastal county (EPA 2023) and contribute to over $9.5 trillion in services and goods (NOAA 2018b). While few coral reefs exist along the U.S. coasts (EPA 2024a) research has found the upper 1-m portion of these reefs significantly reduce flood risk from 100-year storms with benefits of ~$1.8 billion annually from hazard reduction. Florida’s coral reef is the largest in the continental U.S. (The Nature Conservancy 2023) with the five counties in Southeast Florida (figure 1) along the FRT (The Nature Conservancy 2018) being home to over six million people and supporting millions of tourists each year (Florida Department of Environmental Protection n.d.b). The FRT alone plays an important economic role for these residents and visitors as it averts $675 million annually from property damage prevention and protection of commercial activities (The Nature Conservancy 2018).

Tropical storms are one of the most prevalent and costly natural disasters around the world (Reguero et al. 2021) and with warmer temperatures there has been an increase in frequency and intensity over the past 20 years (EPA 2021). Our global sea level is also rising each year due to global warming – our global mean sea level has risen around 8-9 inches since 1880 and has increased fastest in recent decades (Lindsey 2022). Coral reefs are a coast’s first line of defense against storm surge and SLR as they break waves via their structure and friction between the corals and wave energy (van Zanten et al. 2014). Corals can also regrow after storm impact (van Zanten et al. 2014) and have multi-directional accretion which is important as vertical growth will be necessary with rising seas (Burke & Spalding 2022). However, the pace at which SLR is happening is cause for concern as some corals may not be able to keep up. If coral accretion is low their ability to reduce wave energy decreases as depth of water increases (Toth et al. 2023). Traditionally healthy reefs are now being found to have their structural complexity halved and
with more frequent extreme high waves, coastal communities will be at even greater risk of erosion and flood events (Carlot et al. 2023).

4.3. Method

The goal of this synthesis is to answer the question on how coral reefs decrease flood risk from SLR and storm surge to coastlines. This section focuses on the characteristics of coral reefs and why the structure and species composition are significant to understand its capacity for such hazard reduction. Utilizing a predominant meta-analysis provides attenuation rates at various parts of a reef to better understand where future restoration and protection efforts should focus.

4.4. Synthesis

The structural complexity of a coral reef is what reduces wave impact as well as maintain species diversity. Carbonate production needs to exceed erosion rates in order to sustain overall growth, though carbonate budgets are being significantly threatened. One study found Caribbean reefs to be declining by 21% with reduced production from coral bleaching, coral disease, and ocean acidification (Kennedy et al. 2013).

While research shows coral reefs are beneficial for coastal cities such as those in Southeast Florida, the reefs are currently in a steep decline. Calcium carbonate (CaCO\textsubscript{3}) is the building block of coral reefs (Morris et al. 2022) and carbonate budget assessments can provide insight into reef accretion (Toth et al. 2023). Stony corals typically drive reef accretion and a balance between calcification and CaCO\textsubscript{3} erosion through physical and biological processes create an overall positive growth. With coral degradation from disease and bleaching, the reefs have become unbalanced with calcification rates unable to keep up with erosion (Morris et al. 2022). The Florida Reef Tract (FRT) has maintained its function for thousands of years until recent decades. Morris et al. (2022) calculated carbonate budgets at 723 sites along the FRT and determined the northern parts of the reef closest to urban areas have the most degraded
corals. Further south in the Florida Keys, the mid-channel reefs had the highest net carbonate production. Figure 2 provides a linear regression plot to show the relationship between net carbonate production and the percent of live coral coverage across the FRT at the Dry Tortugas (DRTO), Florida Keys (FLK), and Southeast Florida (SEFL). The overall carbonate budget for the entire FRT is in a net erosional state indicating degradation and increased vulnerability (Morris et al. 2022).

Source: Morris et al. 2022

*Figure 2 Relationship between net carbonate production and % of live coral coverage across the FRT.*

Through a meta-analysis of 27 independent studies, Ferrario et al. (2014) assess wave attenuation rates across sections of a reef. The first is the reef flat that stretches out from the
shore, the second is the reef crest which sits at the seaward edge and is the first point of wave break, and the third is the reef as a whole to determine overall wave height and energy reduction. Figures 3 shows an illustration of the different reef sections and figure 4 shows where those sections are found at a reef site in Guam. The findings conclude that wave energy reduction from reef flats, reef crests, and the whole reef (WR) to be 65%, 86%, and 97% respectively (figure 5). Wave height reduction was slightly less, but still significant for flats, crests, and WR with a reduction of 64%, 43%, and 84% respectively (figure 6). Error bars in both figures 5 and 6 indicate 95% confidence interval (Ferrario et al. 2014).

Given the reef crest dissipates the majority of wave energy it plays the most significant role in coastal protection. The upper 1-m portion of a coral reef also plays an important role for U.S. reefs. If the top 1-m of a reef were removed, the 100-year flood range would increase by 23%, the number of people impacted would increase by 62%, building damage costs would increase by 90%, and economic effects from indirect impacts would increase by 49% (Reguero et al. 2021). However, corals are susceptible to sea level rise and with deepening waters their ability to reduce wave energy decreases. Additionally, understanding reef-accretion changes from climate impact, especially those along the reef crest, is pertinent to determining restoration strategies to create more resilient shorelines (Toth et al. 2023).

Source: Ferrario et al. 2014

Figure 3 Cross-section of fringing reef.
Figure 4 Asan Bay, Guam – Whole Reef (WR), Reef Crest (C), Reef Flat (F).

Figure 5 Average wave energy reduction across different reef environments.

Figure 6 Average wave height reduction across different reef environments.
4.5. Discussion

The meta-analysis from Ferrario et al. (2014) remains to be the most commonly cited source amongst coral research when considering their benefits to coastal protection. While some more localized assessments have been executed, it is important to note that more extensive research has not been executed in recent years. Seeing as that the FRT is in a net erosional state it’s concerning to know this natural buffer system may not be able to reduce storm surge and SLR impacts if actions are not taken soon. Understanding where and how a coral reef is able to maximize wave height and energy reduction is pertinent to providing context on restoration plans. This information is also significant to share with stakeholders and promote community engagement around the push for greater coral protection.

5. Status of Southeast Florida’s Coral Reef

5.1. Overview

Chapter 5 answers sub-question 2: What is the status of the Florida Reef Tract? Here I discuss more broadly how coral reefs function under various climatic and human induced stressors. Then I deep dive into the FRT as a whole to understand the current impacts and future risks compromising the reef’s health. The determined problems being faced along the FRT provide context for actions necessary.

5.2. Literature Review

Coral reefs are built when calcifiers produce more calcium carbonate than is removed or eroded (Morris et al. 2022). Since the 1980’s our ocean has absorbed around 30% of anthropogenic CO$_2$ reducing overall ocean pH and making it more difficult for corals to calcify. In tandem with rising CO$_2$ is the increase in our global temperature that has led to more frequent marine heatwaves (IPCC 2019). These high heat events trigger mass coral bleaching that can spread hundreds of kilometers (Blunden et al. 2017). Corals and zooxanthellae have a symbiotic relationship, but when corals become stressed, the algae are expressed from the
coral’s tissue leaving it weak as it lacks its primary source of food. This process is what causes corals to become white or pale thus describing them as bleached. While corals can recover from bleaching, they become more vulnerable in this state increasing their probability of mortality (NOAA 2023).

Coral ecosystems are already reaching their adaptation limits and are expected to decline by 70-90% under 1.5 degree C warming and over 99% under 2 degree C warming (IPCC 2023a). Warm-water coral ecosystems have been determined to be at a significant risk of species and biodiversity loss (IPCC 2023b). The IPCC has four GHG emissions scenarios called Representative Concentration Pathways (RCP). An RCP 4.5 is an intermediate GHG reduction scenario where if implemented warming would be “more likely than not to exceed 2 degrees C” by the end of the 21st century (IPCC 2014). Tropical coral reefs are facing greater climate threats than the deeper, cold-water corals and even in the RCP 4.5 scenario, coral reefs are likely to be eradicated by 2040-2050 (Hoegh-Guldberg et al. 2017).

The FRT is not only suffering from climate change impacts, but also from disease, coastal construction, pollution (Wusinich-Mendez n.d.), increased sedimentation and suspension, runoff, upwelling, and stress (Collier et al. 2008). Acropora corals, an important reef-building coral (Toth et al. 2023) have seen significant declines from tissue loss disease (TLD) in previous decades. However, a more recent and massive outbreak of stony coral tissue loss disease (SCTLD) has swept across the entirety of the FRT and other territories, making it one of the biggest threats U.S. reefs face today (Wusinich-Mendez n.d.).

Contamination is another major problem to coral reefs and can stem from various types of pollutants. Poor sewage systems and storm runoff can bring harmful waste and freshwater into coral systems, and nonpoint sources such as agricultural runoff can carry herbicides and chemicals into the waterways leading out to the ocean. Each of these pollutant sources all negatively impact corals such as freshwater increasing coral vulnerability, nitrates and phosphates contributing to bleach events, disease outbreaks, and increased algal growth, and
endocrine disruptors are hindering coral growth (Carlson et al. 2022). Nutrient loading on marine ecosystems can also trigger harmful algal blooms (HABs) which are caused by excess growth of algae that can have toxic effects on marine species and humans (NOAA 2023). HABS also decrease available oxygen in the area causing problems for whole reef ecosystems (NOAA 2016).

Data collected by Towle et al. (2020) for NOAA’s Coral Reef Conservation Program from 2014-2018 determined highly populated coastal areas in Florida relates to increased negative impacts on reef health as indicated by figure 7. Their assessment found that the FRT is 69% impaired overall (figure 8). The percentage is based on a framework looking at four key areas including climate, corals and algae, fish, and human connections. The four groups are then broken down into 16 specific reef health indicators such as coral cover, temperature stress, fish species diversity, and human awareness. The four mainland counties (Martin, Palm Beach, Broward, and Miami-Dade) show correlation between high population and high reef impairment ranked at 62% impaired (figures 7 and 8) while the Florida Keys and Dry Tortugas show correlation with low population and fair reef health ranked at 71% fair and 73% fair respectively (figure 8) (Towle et al. 2020).

Coral diversity is important as the structural complexity plays a key role in wave attenuation (Harris et al. 2018) and helps support a healthy ecosystem (Graham & Nash 2013). The friction created between the reef’s rigid build and the energy of a wave dissipates its impact. Where friction is reduced, larger waves occur leading to greater erosion of the near shore reef and coastlines (Harris et al. 2018). Early research also explains the significance of complex reef structures for fish diversity (Graham & Nash 2013). The various shapes and formations of the corals can help mitigate excessive competition or predation in order to create balance and enhance the number of fish species (Darling et al. 2017). A healthy reef with a high variety of fish populations is important for the FRT as the tourism and fishing industries provide billions of dollars in economic activities annually (The Nature Conservancy 2018).
Figure 7 Relation between population density and reef health at FRT.

Figure 8 FRT health ranking across three sections (Dry Tortugas, Southeast Florida, Florida Keys) and the overall reef.
5.3. Methods

This environmental assessment looks primarily at present impacts and considers future risks to determine their level of concern. I ranked each key factor based on an evaluation of each topic through existing literature and research. I chose to assess climate impacts, coral diversity and disease, pollution, and direct human activity as they are the most common problems reported across various literature read for the purpose of this paper. Based on the findings, I have ranked each factor as high, moderate, or low (most concerning to least concerning) to guide actions and recommendations.

5.4. Environmental Assessment

I present in table 1 a breakdown of each factor, its impacts and risks, and its ranking of concern based on the analysis proceeding. The analysis goes into detail of what has occurred over the past decade, what is currently happening, and considerations for what may happen in the future. It’s important to note that while “direct human activity” is ranked as low, it does not mean it is not a problem, but that its impacts are more manageable and the risks are easier to mitigate.
Table 1 Key factors, impacts, and risks for assessing FRT status.

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>Current Impacts</th>
<th>Future Risks</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Change</td>
<td>- Rising CO\textsubscript{2} emissions</td>
<td>The continuation and exacerbation of the current impacts will increase risks to the FRT. The likelihood for bleaching and storm events both in scale and time increase if CO\textsubscript{2} emissions continue to grow.</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>- Heat stress &amp; bleaching</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Storms</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Ocean acidification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coral Diversity &amp; Disease</td>
<td>- White Plague Disease</td>
<td>Increasing frequency in heat and coral bleaching will leave coral reefs vulnerable to various diseases. Increased loss of keystone species such as the <em>Acropora</em> genus and other reef-building corals can change overall structure and system of the reef, reducing its ability to protect coastlines from SLR &amp; storm surge.</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>- Black Band Disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Stony Coral Tissue Disease Loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pollution</td>
<td>- Effluent, pesticide, debris, and chemical runoff</td>
<td>Lack of sewage system replacements will continue to cause effluent spills and runoff. In addition to infrastructural problems, climate change will continue to cause sea levels to rise bringing groundwater to the surface increasing flooding and runoff. Each of these aspects can also lead to more frequent and intensified harmful algal blooms.</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>- Groundwater contamination</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Poor sewage systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Human Activity</td>
<td>- Sedimentation</td>
<td>Continued disinterest or ignorance from cities and companies looking to expand coastal commercial operations puts the reef at greater risk of sedimentation and boat incidents. Additionally, the absence of sufficient community outreach and education will perpetuate the way humans interact with the reef and fail to advocate for greater protection.</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>- Anchor drop</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Uneducated reef users (scuba diver, snorkeler, etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Trapping &amp; fishing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4.1. Climate Change

Increasing heat has caused corals to become stressed leading to large bleaching events (IPCC 2023a). Figures 7 and 8 show the portion of the reef along the Florida Keys being ranked as fair at the time of study (2014-2018), however satellite recordings from July 2023 documented the hottest ocean surface temperatures on record around Florida (Lindsey 2023). This heat wave triggered an Alert Level 2 (table 2) was put in place for the entire Florida Keys meaning extreme coral bleaching and high coral mortality to be likely (NOAA n.d.). Florida will need to reassess its rankings along the entirety of the FRT in order to determine its current health status.

These increasing sea surface temperatures are also causing tropical storms and hurricanes to become both stronger and more frequent (Mousavi et al. 2011). While corals can reduce storm impact, intensified storms may be a problem for the future of Florida’s coral reefs as the coral can become damaged from more forceful wave energy. An impact such as this can cause small cracks and broken pieces, or even displace an entire coral colony (NOAA 2018a). In 2017 Florida was hit with major storms that negatively impacted the FRT. Through diver surveys it was determined Acropora cervicornis and Orbicella annularis, both of which are listed on the Endangered Species Act, were hindered most (NOAA 2018a).

Rising temperatures and increased ocean acidification affect coral species differently. In a lab experiment studying reef composition from the Florida Keys, 12 common corals of this area were examined for two months under two temperatures of 27 and 30.3 degrees C, and under partial pressure CO₂ (pCO₂) levels of 400, 900, and 1300 µatm. The goal of this experiment was to understand the possible make-up of the reef under future climate scenarios. Some of the most abundant corals, Orbicella faveolata, Montastraea cavernosa, and Porites astreoides, were most negatively impacted by higher temperature and pCO₂. Under the business-as-usual scenario (if CO₂ emissions continue at current rates) the reefs mainly comprised by these corals are projected to have 50% higher reduction in calcification by the end of the century. However, under a reduced CO₂ emissions scenario, calcification rates by 2100 would decline by less than 20% (Okazaki et al. 2017). Current and future risks on coral reefs from continued CO₂ emissions
should provide guidance on how and why emission reductions are necessary as part of the protection process for this ecosystem.

Table 2 Alert system for coral reefs under heat stress.

<table>
<thead>
<tr>
<th>HEAT STRESS LEVEL</th>
<th>DEFINITION</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Stress</td>
<td>- Sea Surface Temperature (SST) is below the Maximum Monthly Mean (MMM) and the Bleaching Threshold temperatures. - HotSpot is less than or equal to 0.</td>
<td>No heat stress or coral bleaching is present.</td>
</tr>
<tr>
<td>Bleaching Watch</td>
<td>- SST is above the MMM, but below the Bleaching Threshold. - HotSpot is greater than 0 but less than 1.</td>
<td>Low-level heat stress is present.</td>
</tr>
<tr>
<td>Bleaching Warning</td>
<td>- SST is at or above the Bleaching Threshold. - HotSpot is equal to or greater than 1. - Degree Heating Week (DHW) is greater than 0 but less than 4.</td>
<td>Heat stress is accumulating; coral bleaching is possible.</td>
</tr>
<tr>
<td>Alert Level 1</td>
<td>- SST is at or above the Bleaching Threshold. - HotSpot is equal to or greater than 1. - DHW is equal to or greater than 4 but less than 8.</td>
<td>Significant coral bleaching is likely.</td>
</tr>
<tr>
<td>Alert Level 2</td>
<td>- SST is at or above the Bleaching Threshold. - HotSpot is equal to or greater than 1. - DHW is equal to or greater than 8.</td>
<td>Severe coral bleaching and significant coral death (mortality) is likely.</td>
</tr>
</tbody>
</table>

5.4.2. Coral Diversity & Disease

The FRT is comprised of various coral species with over 45 types of stony corals and 35 types of octocorals (Florida Department of Environmental Protection n.d.a). *Acropora cervicornis* and *Acropora palmata* are two of the most vital reef-building corals, but due to such a large decline from disease and heat stress both have been listed on the U.S. Endangered Species Act as “threatened” (van Woesik et al. 2020). According to van Woesik et al. 2020 the authors determined *Acropora cervicornis* to be one of seven species of coral most susceptible to environmental changes. They also concluded *Acropora cervicornis* to have one of the least suitable habitat areas limiting its ability to grow across the reef tract as a whole (van Woesik et al. 2020). Climate change is suspected to exacerbate the spread of disease. One assessment looking at the FRT from 2005-2015 that found disease was highest during the record warmest years of 2014 and 2015 (Van Woesik & McCaffrey 2017). In those two high thermal heat years multiple diseases swept across the FRT including white plague disease (WPD), black band disease (BBD), and stony coral tissue loss disease (SCTLD).
In a study running from October 2013 to July 2015, along the FRT portion that lines Miami-Dade County, found the highest coral bleaching event to occur September 12, 2014. Of the 25 corals assessed that day, 84% exhibited bleaching and exactly two weeks later WPD was found at the monitoring sites. After just 12 months WPD spread north and south by 100km and 30km respectively. Over this period, stony corals were predominantly burdened with the brunt of the impact on *Eusmilia fastigiata*, *Meandrina meandrites*, and *Dichocoenia stokesi* decreasing their populations to less than 3% (Precht et al. 2016).

BBD is another common disease impacting various species around the world and a major issue for reef-building coals. Increased temperatures, nutrients, and light exposure all contribute to the rate of BBD growth. This disease most commonly occurs along the FRT during the warmer water seasons where temperatures surpass 29 degrees C. Ocean temperatures surpassed 30.5 degrees C for weeks at a time in 2014 and 2015 which impacted a variety of corals. *Dendrogyra cylindrus* was one of the species affected and though not a key reef builder, still provides a vertical design creating a unique habitat setting. While *Dendrogyra cylindrus* is susceptible to coral diseases, it wasn’t until 2014 and 2015 where BBD was first documented on this species in the FRT. This species was listed as threatened at the federal level in the U.S. in 2014 given its declining population in addition to extreme fragmentation contributing to poor recruitment rates (Lewis et al. 2017).

In 2014, stony coral tissue loss disease (SCTLD) was first discovered along Florida’s reef and is thought to be caused by a bacterial pathogen (UN Environment Programme 2020) though the exact etiology is still unknown (Landsberg et al. 2020). The initial spread of SCTLD appears to coincide with sedimentation from dredging as well as a mass bleaching event (Miller et al. 2016, Landsberg et al. 2020). The spread of SCTLD occurred rapidly with disease detected across the entire reef in just a seven-year span as shown in figure 9 (Florida Keys National Marine Sanctuary n.d.). Out of the 45 types of coral along the FRT, 22 are negatively affected by SCTLD (Meyer et al. 2019) five of which are listed under the ESA including *Dendrogyra cylindrus*,


*Mycetophyllia* spp., *Orbicella annularis*, *Orbicella faveolata*, and *Orbicella franksi* (Florida Keys National Marine Sanctuary n.d.). Though it appears this particular disease does not impact *Acropora cervicornis* or *Acropora palmata* (Meyer et al. 2019) SCTLD remains a major concern as coral mortality rate increases and can lead to death in as little as a few weeks (UN Environment Programme 2020).

*Figure 9 Map of stony coral tissue loss disease at the FRT from initial detection in 2014 through 2020*
5.4.3. Pollution

Of the total population in Martin, Palm Beach, Broward, and Miami-Dade County (Figure 1) 57% utilize a centralized sewer system and 43% depend on underground wastewater disposal where water may be treated or untreated. Of that 43%, 23% of the wastewater goes through a septic tank system while the other 20% is released via injection wells (Futch et al. 2011). Lack of modernization of these wastewater systems has led to pollutants leaking directly into marine waters (The Nature Conservancy 2018). Various sewer outfalls are positioned around Southeast Florida with 4,800 just in Broward County. With increasing heavy rains, the storm-water funnels through these outfalls often carrying various surface pollutants such as pesticides, road debris, and chemicals into the coastal environment (Futch et al. 2011).

Florida has had many sewage failures increasing nutrient loading in its surrounding coastal ecosystems. The St. Lucie Estuary which leads out to part of the FRT has had consistent problems with their “on-site sewage treatment and disposal system” also referred to as a septic system. Tests found waters close to residential buildings constructed prior to 1978 to have higher concentrations of dissolved nutrients in the nearby groundwater and surface water. Additionally, percentages of macroalgae and phytoplankton related to nitrogen (N) from sewage were comparable to published ranges found in areas with septic contamination. This type of effluent leads to increasing numbers of HABs impacting the local reef system (Lapointe et al. 2017). HABs occur as algae rapidly grow to unnatural numbers (NOAA 2016).

Injection wells are intended to maintain wastewater in the aquifer zone where effluent is injected into the aquifer without it moving into other overlying zones or seeping into surface water. However, there is a lack of monitoring of surface waters to determine whether or not these systems are functioning as planned. Class I and Class V injection wells discharge into permeable aquifer systems where if piping becomes leaky, may seep through the aquifer and into marine waters. Not only is effluent from municipal sewage systems injected into the aquifer systems, but so is waste from cruise ships. Monitoring and regular testing of Class I
injection wells is carried out with the purpose of maintaining a potable water source rather than possible environmental contamination. Regulations neglect to consider various flow direction and the possibility of submarine groundwater discharge carrying injected wastewater. Figure 10 shows the locations of both types of injection wells across Miami-Dade and Monroe County (Bacchus et al. 2014).

Groundwater discharge is of increasing concern as it greatly contributes to harmful algal blooms (HABs) particularly from nutrient loading of nitrogen (N) and phosphorus (P). SLR will infiltrate the groundwater raising it up and allowing it to flow out into the surrounding environment, transporting contaminants into waterways (Hill et al. 2023). These blooms can produce toxins and illnesses to both marine species and humans. Even if a bloom is not toxic, the surplus in algae decreases oxygen creating a hypoxic environment that decays water health and suffocate corals (NOAA 2016). An experiment in Key Large showed high N and P increase coral bleaching 3.5-fold and increase coral disease severity 2-fold thus showing high degradation rates from pollution runoff (Bacchus et al. 2014).

Figure 10 Map of Class V (yellow) and Class 1 (pink) injection wells across Miami-Dade County and Monroe County

Source: Bacchus et al. 2014
5.4.4. **Direct Human Activity**

In Florida, lobster and crab traps have caused harm to the coral reef and the surrounding marine life when dropped inadvertently on this delicate habitat. During storms, strong currents, or other movement from boats and human interactions the traps hit against the corals causing breakage. Hook and line fishing is another problem as the line and tackle get tangled and hooked onto the stony corals. Plus, divers, swimmers, and snorkelers, without proper training or lack of understanding, may stand, kick, or grab corals further damaging the reef. Reef users at times also accidentally drop anchors on the reef, leave trash or debris, and even cause chemical harm from the sunscreen used before entering the water (The Nature Conservancy 2018).

Larger scale human impacts from commercial expansion such as dredging and shipping are increasing coral burial through sedimentation and increasing anchoring incidents. The Port of Miami, Port Everglades, and Port of Palm Beach have grown significantly with increasing cruise ships and freight carriers coming in and out of Southeast Florida and amassing to greater possible risks to the local marine habitats (Walker et al. 2012). From 2013-2015 the Port of Miami dredged the channel to expand it both vertically and horizontally. This project impacted the Inner Reef north with sedimentation altering biological responses and increasing partial mortality. Sedimentation was later found outward 700 m from the channel though the original monitoring put in place for the project only extended 50 m (Miller et al. 2016).

5.5. **Discussion**

Climate change, disease, pollution, and human activity all play a role in the declining health of Florida’s coral reef. Based on these components it’s evident the FRT has been negatively impacted and will continue to be at risk of further damage if changes aren’t made. Many of the coral species have seen sharp declines due to disease and thermal stress, and the structural complexity of the ecosystem will continue to be altered if emissions aren’t reduced. If the FRT changes drastically it may not provide sufficient habitat or food to other species that rely on a
flourishing ecosystem, the economic benefits the reef currently provides may be stifled, and coastal flood risks will likely increase.

Though figures 7 and 8 show the portion of the reef along the Florida Keys being ranked as fair at the time of study (2014-2018), it is likely this is now in impaired or critical condition as satellite recordings from July 2023 documented the hottest ocean surface temperatures on record around Florida. Though the alert for high coral mortality was created in the Florida Keys, it can be inferred these high temperatures may have also impacted portions further up the FRT during that summer heat wave.

Many of the problems the FRT faces are heightened by one another. Increased ocean temperatures cause bleaching leaving the corals more susceptible to disease. Additionally, with increasing climate change causing large flooding events there is increased chances in groundwater release, sewage breaks, and surface run-off. The harmful pollutants associated with these types of discharge can also increase susceptibility to coral disease and reduce overall coral health. The information provided in both this chapter and chapter 7 on the frequency of sewage spills and run-off suggests a dire need for updated infrastructure to help mitigate future risks.

Direct human activity is the one category that doesn't necessarily impact the other categories, though is still important to address. The way people interact with the reefs and the information they are provided, or lack thereof is evident in the way many people interact with this ecosystem. Greater public outreach should be considered for people to interact safely with the FRT as well as more stringent fishing, boating, and trapping regulations.
6. Benefits of the Florida Reef Tract for Disadvantaged Communities

6.1. Overview

Chapter 6 answers sub-question 3: How can healthy coral reefs provide benefits to disadvantaged communities in Southeast Florida? In this section I address what Environmental Justice (EJ) entails and its importance in answering the overarching question of this paper. An EJ analysis emphasizes the injustices being faced in Southeast Florida and the importance coral reefs play in reducing flood risks. The goal of this section is to broaden the discussion around EJ in Florida and to bring more data forward to create better policy decisions and reduce burdens on disadvantaged communities.

6.2. Literature Review

Environmental justice is defined by the EPA as “the just treatment and meaningful involvement of all people, regardless of income, race, color, national origin, Tribal affiliation, or disability, in agency decision-making and other federal activities that affect human health and the environment...” (EPA 2024b). This definition is further defined to include that fair treatment means “no group of people should bear a disproportionate burden of environmental harms and risks, including those resulting from the negative environmental consequences of industrial, governmental, and commercial operations or programs and policies” (EPA 2016). Vulnerable populations are often more impacted by climate change as they are unable to protect themselves or families from worsening conditions (WHO 2023). Nearly 40 percent of those residing in a coastal county in the U.S. fall into a high-risk category for coastal hazards – this includes children, elderly, people living in poverty, and minority groups (NOAA 2018b). People who live in low-lying coastal areas tend to be at greatest risk from natural hazards, SLR, intensified storms, and stronger ocean waves (Reguero et al. 2021).
Across three major districts in Southeast Florida – Miami-Dade, Fort Lauderdale, and West Palm Beach – combined account for ~6 million people and make up one of the most ethnically diverse areas. Of all residents in those districts, Hispanics and non-Hispanic blacks comprise 43% and 20% of the population respectively (Collins et al. 2018). In Miami-Dade County alone permanent inundation from 1-2m of SLR could impact 54.7% of residents and from 3m of SLR impact 92.2% of residents. Miami-Dade County is considered one of the most racially inequitable cities with close to 50% of the residents working for low wages (Steetram et al. 2023).

Florida’s low-lying land puts it at heightened risk to climate change impacts. One model by Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (2020) shares different projections of median to high possibilities of SLR near Key West, FL based on data from the IPCC and the National Oceanic and Atmospheric Administration (NOAA). Figure 11 shows sea level data and projections from a tide gauge in Key West beginning at zero in 2000. These predictions vary based on emissions scenarios and show SLR could be significantly reduced if GHG emissions are significantly reduced. The IPCC median scenario (Growing Emissions Scenario) projection represents the lowest boundary. The NOAA Intermediate High represents the “upper boundary for short-term use until 2070,” the NOAA high projection is intended to be used for “projects within a short-term planning horizon,” and the NOAA extreme is used as a possible scenario for SLR in an extreme ice melt scenario. The extreme curve is to show a tentative upper limit but is not used under application (Southeast Florida Regional Climate Change Compact Sea Level Risk Work Group 2020).

From 2000 to 2017 SLR in Key West increased 3.9 inches and in just 16 years SLR could increase another 10-21 inches (figure 11). Challenges are already being faced as SLR impacts the livelihood of people, the economy, and the environment. The added stressors from storm impact are creating even greater disparities on communities through displacement, a drop in property value, rising insurance costs, and damage to homes, roads, and other important infrastructure (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group
These climate risks being faced are leading to “climate gentrification.” Traditionally, gentrification happens when affluent people move to areas comprised of low-income families causing costs to significantly increase, displacing the original residents and business owners. Now, with climate change many of the higher income residents are shifting their desired housing location to lower climate risk zones often housed by low-income people (Hu 2020).

![Figure 11 Sea level data and projections from tide gauge in Key West beginning at zero in 2000.](source)

### 6.3. Method

An Environmental Justice (EJ) analysis is typically used to identify disproportionate impacts on a racial, low-income, or indigenous group. Disproportionate environmental hazards are often located in these communities. Climate and environmental stressors can include exposure to poor air quality and pollutants, limited access to green spaces or healthy foods, or poor infrastructure. The goal of this EJ analysis is to use the information collected to create
meaningful involvement both from the EJ communities and stakeholders to promote equitable decision making (EPA 2014).

I carried out my own Environmental Justice analysis through data collection and examination of burdens endured by disadvantaged groups in Southeast Florida and the future risks they face. My analysis utilizes a study by Reguero et al. (2021) on the risks of 1-m reef loss and implications for inland flooding. Additionally, I look more closely at one county in particular, Miami-Dade, to understand demographics based on various elevation zones. I prepared a census table (table S.1) for each of the municipalities and then determined the risks of climate gentrification and flooding.

6.4. Environmental Justice Analysis

6.4.1. Overview

In an analysis from Reguero et al. (2021), the authors assessed the value coral reefs provide through flood risk reduction in the U.S. including both U.S. states Hawaii and Florida, and the U.S. territories Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands. The calculations are based on 1-m loss in reef height to determine changes in coastal flooding and disadvantages that would be endured. Shown in figure 12 is the flood risk of an area in Key West, Florida that displays how the 100-year storm map would change, extending further inland in a 1-m reef loss scenario. Figure 13 shows a snapshot of that area determining the overall cost benefit of protection under the same reef loss scenario. Part of the analysis found flood risk reduction from the existing coral reef to benefit 5,663 people, avert $356 million in direct infrastructure damage, and prevent $316 million in economic disruption in Southeast Florida. Vulnerable populations including children, elderly, low-income, and minority groups benefit significantly from coral reefs. However, in the 1-m reef loss scenario the annual risks increase by ~50% for children, ~100% for elderly, ~110% or low-income people, and ~80% for minority groups in Florida relative to the other U.S. states and territories with coral reefs (Reguero et al. 2021).
The reefs along the mainland portion of Florida in highly developed areas provide the majority of economic benefit. Miami for example receives greater risk reduction than the Florida Keys despite the corals in the Keys being larger than the rest of the FRT. Of all locations assessed, Hallandale Beach bordering the Miami-Dade and Broward County line in Florida ranked number one for having the largest population with the greatest risk reduction by the FRT and number three for greatest economic value from the FRT (Reguero et al. 2021). Hallandale Beach has a population of 41,202 with ~19% identifying as Black or African American and ~39% identifying as Hispanic or Latino with a total median household income of $45,417 and poverty rate of ~21% (U.S. Census Bureau 2020).

![Image](a)

Source: Reguero et al. 2021

**Figure 12** 100-year flood risk with current reefs and with 1-m reef loss in Key West, Florida.

![Image](b)

Source: Reguero et al. 2021

**Figure 13** Cost benefit of damage prevention from current reefs versus under 1-m reef loss.
6.4.2. Flood Risk
The two neighborhoods within Miami-Dade County with evident climate disparities are Opa-locka and Hialeah. Most of southeast Florida sits on extremely porous limestone that provides majority of its people with drinking water (Cleetus et al. 2015). While both Opa-locka and Hialeah sit at the mid-range of elevation for their county (figure 14), the compounding effects of SLR causing the water table to rise, and increasing hurricanes and storm surge puts these neighborhoods at greater risk of inland flooding. These two areas are known for their economic struggles and lack of health care making the need for climate resiliency even more important (Cleetus et al. 2015).

95% of Hialeah’s population is comprised of Hispanic or Latino identifying persons with an average income of ~$50,000 and an 18% poverty rate. Opa-locka’s population is comprised of 47% Hispanic or Latino and 52% Black or African American identifying persons with an average income of ~$30,000 and a 28% poverty rate (table S.1). More frequent flood events and lack of government support from agencies like FEMA places greater stress on the residents of these neighborhoods. Elderly people in multi-family buildings in particular struggle with increasing flood and storm impacts as assistance is not regularly received and they are often not mobile enough to go out and collect supplies necessary (Cleetus et al. 2015).

6.4.3. Climate Gentrification
Minority groups in Southeast Florida primarily live in inland flood risk zones with little coastal amenities while the more affluent members of the community, often non-Hispanic whites, live in flood risk areas, but with greater coastal amenities. The economically advantaged groups also tend to have greater access to flood mitigation or resiliency tools as they can afford rising insurance costs, make modifications to their homes, and use their social power for increased government support (Maldonado et al. 2016). However, growing concern around rapidly increasing climate impacts on Southeast Florida has sparked discussion around the possibility of climate gentrification.
Climate gentrification happens when affluent residents leave their neighborhoods to seek higher elevation to avoid risks associated with SLR and erosion. The areas infiltrated tend to be comprised predominantly by low-income people of color. The original residents are then displaced because cost of living and property values increase rapidly and drastically (Hu 2020).

In a research letter from Kennan et al. (2018) the authors provide a conceptual model to consider the climate resiliency of different neighborhoods in Miami-Dade County to understand how this may alter the property market. It is suspected that higher elevated properties in Miami-Dade County will become more valuable over time as they will provide greater protection against flooding events and SLR. Figure 14 shows the neighborhoods in Miami-Dade County and their corresponding elevation range (Keenan et al. 2018).

Utilizing the elevations presented in figure 14, I collected data shown in table S.1 providing the population and demographics of each municipality within Miami-Dade County to better understand which groups would be at most risk to climate gentrification. Table S.2 shows the sums and averages of the populations and demographics respectively for the first half of the data (low to mid elevation) and the second half (mid to high elevation). These averages show there is a greater number of people overall in the second half of the dataset and the number of people who identify as Black or African American increase with higher elevation as well. This indicates a higher risk of climate gentrification for this particular demographic.

Additionally, the average percentages for income and poverty decrease and increase from the low to mid elevation group and the mid to high elevation group respectively. Meaning those in higher elevation have less passive income and the likelihood of poverty increases. In the mid to high elevation group, it’s important to also note that the two outliers where median income is above $100,000 (Pinecrest and Miami Shores) both have the highest percentage of people identifying as white alone and the lowest poverty percentages.
Figure 14 Neighborhoods in Miami-Dade County and their corresponding elevation.
6.5. Discussion

Based on the EJ analysis, various neighborhoods in the county of Miami-Dade will face climate inequities as climate change continues. The data from figure 14 coincides with the information presented from both Reguero et al. (2021) and Keenan et al. (2018) as those more inland or in higher elevation will have an increased risk in flooding and hazards under a 1-m reef loss scenario and 1-2-m increase in SLR. These risks amplify the possibility of climate gentrification for lower income people of color as the more affluent coastal dwellers may look to shift to higher elevation points to avoid increasing climate threats. However, little data has been presented to promote the discussion of EJ in Southeast Florida. It will be important for research to determine the various elevation points in the remaining counties along the FRT. Then the same assessment I did could be carried out utilizing census data to better understand which regions and peoples will be at greatest risk of climate impacts. This information can promote greater climate action for agencies such as FEMA and help push for more inclusive policy to reduce climate burdens on disadvantaged communities.

7. Actions Needed for Protection & Restoration of Florida’s Coral Reef

7.1. Overview

Chapter 7 answers sub-question 4: What actions are needed to protect the Florida Reef Tract and the climate resilience it provides? In this section I discuss risk management strategies for protecting and restoring the FRT. Additionally, this section helps guide many of the recommendations made following this chapter.

7.2. Literature Review

Corals are expected to seriously decline with 1.5-2 degree C increase in global temperatures (IPCC 2023b). For coral restoration to succeed more stringent policy is needed to reduce further
coral loss (Carlson et al. 2022). Drastically reducing GHG emissions to avoid further temperature increase is essential to improve overall ocean and reef health globally (United Nations 2022). More localized approaches are also needed to coral reef health and coastal cities. These strategies can include filling policy gaps, putting coral restoration as an incentive for insurance plans, and enforcing stronger wastewater management (Carlson et al. 2022).

In Florida in particular, the economic benefits of its coral reefs are often overlooked, but if included into policy decisions across various government levels it could help promote sustainable funding for the reefs and those that rely on them. Increasing advocacy from reef stakeholders such as individual and commercial fisher people, divers, and tour guides can promote further protection and restoration. Defining the ecosystem services coral reefs provide and communicating up to date data to policy makers can provide greater policy support (The Nature Conservancy 2018).

7.3. Methods

This section provides an analysis on risk management strategies to determine necessary actions to reduce current impacts and curtail future risks to the FRT. Through various syntheses and case studies, I evaluate the following categories: GHG reduction, restoration, local, state, and federal policy and management, and enhanced local infrastructure. Each of these aspects relate to one another and will be important in the success of reef restoration. These categories were selected based on the findings from chapter 3 that conclude the biggest problems threatening the FRT’s health based on the most reported problems from research analyzed for the purpose of this paper. I created figure 15 to show the four categories assessed in this section with GHG reduction and coral restoration in the darker green color representing actions with long term results – meaning it may be decades before changes are visible. Sewage infrastructure and policy and management designated in the light green color represent management strategies with results seen in the short term of just a few years. The arrow shows the relation between all four categories as lowering carbon dioxide (CO$_2$) will help reduce coral stress and allow for greater success of restoration. Replacing or enhancing local sewage infrastructure will also
reduce pollution from harming restored corals. Policy and management will help promote continued protection and restoration to maintain the overall efforts of the other three categories.

The GHG reduction section is a brief synthesis of the importance of carbon reduction as a way to promote the long-term health of corals. This is a short section as the impacts of CO$_2$ on coral reefs is discussed in detail throughout this paper. However, it is foundationally important for the other strategies presented and is a key factor for the future of coral reefs.

For restoration, I predominantly use a single case study highlighting coral restoration in the U.S. Virgin Islands to determine its potential to reverse coral degradation and maintain the ecosystem’s functions. This particular data was selected as the reefs around the U.S. Virgin Islands and Southeast Florida have similar features. The analysis also considers restoration management specifically for the *Acropora palmata*, a prevalent and important species for both the U.S. Virgin Islands and the FRT. The findings provide guidance on recommendations and strategies Florida could implement for coral restoration.

The sewage infrastructure section focuses on an analysis of various pollutants from sewage discharge and their fate on reef health. I utilize current events from the past five years of sewage spills into Southeast Florida’s waterways to show the impacts various compounds can have on the FRT. It also highlights the frequency of such spills and urgency for sewage infrastructure overhauls. The final section on policy and management, I perform a policy gap analysis to show where corals can be considered in existing policies and plans. I also consider action at both a local and global scale through a synthesis of literature.
7.4. Mitigation & Risk Management Assessment

Figure 15 shows the four key strategies discussed in this section to enhance restoration efforts and protect the FRT. These components each play a role in the success of the other and provides a comprehensive management approach.

Figure by Michaella Sena 2024

Figure 15 Risk management strategies to protect and restore the Florida Reef Tract.

7.4.1. Greenhouse Gas Reduction

Increasing anthropogenic emissions, particularly CO₂, has changed the chemical makeup of our ocean and has lowered its overall pH, making it more difficult for calcifying species such as corals to build their structure (IPCC 2019). Additionally, CO₂ is increasing our global temperature and thus sea surface temperatures, which lead to coral stress and bleaching (IPCC 2023a). Extreme warming events are expected to increase in frequency and severity due to increasing GHG emissions. Given the amount of accumulated CO₂ in the atmosphere from more than a century of emissions, temperatures would continue to rise and trigger extreme warming events for decades even after emissions are cut (Ortiz et al. 2014). An analysis looking at Caribbean reefs highlights the significance of combining both local actions and a low-carbon
economy in order to mitigate further reef loss and ecosystem services (Kennedy et al. 2013). A low-carbon economy means there would need to be significant emission reductions and lowered radiative forcing to keep global warming below 2 degrees C (Kennedy et al. 2013).

7.4.2. Restoration

Focus on coral restoration has become of increasing interest as extensive habitat loss continues to plague coral ecosystems. Due to a divide between various practitioners, managers, and scientists, few specified restoration plans have been designed or assessed for the long-term climatic impacts projected to occur (Boström-Einarsson et al. 2020). An analysis from Toth et al. (2023) provides useful insight into restoration actions based on their research at a particular site in the U.S. Virgin Islands. This study is important as this particular reef system is similar to the FRT and serves as an example of how Florida can implement restoration plans and what the outcome could be if the state were to adopt the strategies presented.

Reef elevation and its structural complexity have been significantly reduced from anthropogenic climate change and impacts. The majority of wave attenuation occurs along the shallow points of a reef crest and serve as the main point for coastal protection. *Acropora palmata* has played a key role in reef construction in the western Atlantic for thousands of years as they have both a strong structure and rapid accretion rate. However, coral disease and warming waters have led to a massive decline in *Acropora palmata*, changing the overall structure and functions of the ecosystem with reef crests being much flatter and deeper than before. Carbonate budgets help determine accretion-erosion rates and how coral restoration can be most successful in rebuilding a supportive coral ecosystem. However, few studies have addressed carbonate budgets in conjunction with increasing water levels along reefs to determine the capacity for coastal protection (Toth et al. 2023).

The analysis from Toth et al. (2023) studies the Buck Island Reef National Monument (BIRNM) and analyzes carbonate budgets across 54 sites. BIRNM is characterized as a barrier reef and has helped buffer coastal erosion until the 1950s when the northwest part of the island began
to see a reduction in beach habitat. This beach is not only important from a historic and cultural perspective, but also provides economic support, and nesting grounds for endangered sea turtles. Of the 54 sites studied at BIRNM, only five had positive accretion potential with the southern portion of the reef crest having significantly higher accretion rates than the rest of the reef due to higher coral cover allowing for greater overall carbonate production. Bioerosion made up 91% of the process across the reef sites. The positive reef accretion in the southern reef though was due to an almost negligible elevation change projection of +1 cm by 2100 versus substantial erosion of -13.09 cm by 2100 across the other sites. Acropora Palmata and a few other coral species play a substantial role in carbonate production, but their abundance is what determine carbonate production across the various sites thus explaining the greater production in the southern reef crest (Toth et al. 2023).

After their initial assessment of the reef the authors of Toth et al. (2023) performed an experiment from 2019-2021 to conclude coral growth potential through restoration at BIRNM. In the initial transplant of Acropora palmata found 14 of 30 died due to an early heatwave causing thermal stress on the coral. However, the following two years showed overall success with the death of only one colony. Through a population model, the team determined if an individual, but large-scale restoration effort of planting Acropora palmata could happen by 2030 then coral cover would increase across the reef crest for the subsequent 20 years. On the high end if restoration efforts could successfully outplant 500,000 Acropora palmata then its projected cover would increase by 42.4%. If restoration or reproduction were to end in 2050, then the species would continue to die and gradually diminish mainly due to climate change. If 500,000 Acropora palmata were in fact planted, then over 30% cover and 10% elevation would remain until 2100. Figure 16 provides an illustration of Acropora palmata growth over two years to show its ability to grow rapidly and increase coral cover. Figure 17 shows the mean increase in Acropora palmata showing percent cover on the reef crest at BIRNM under three restoration scenarios and post restoration mortality scenarios until 2030 and projections of success until the end of the century. The horizontal line in figure 17 shows minimum increase
necessary for *Acropora palmata* cover for reef-accretion to keep up with the lowest SLR projections by 2100 (Toth et al. 2023).

**Figure 16** Two-year time-series of *Acropora palmata* growth at BIRNM.

**Figure 17** Mean increase in *Acropora palmata* showing percent cover on the reef crest at BIRNM under three restoration scenarios and post restoration mortality scenarios until 2030.

### 7.4.3. Sewage Infrastructure

Septic systems in Florida leak pollutants into the groundwater that eventually run into the ocean (The Nature Conservancy 2018). Sewage discharge into waterways causes a variety of concerns for reef health as it contains various compounds including, but not limited to freshwater, endocrine disruptors, and inorganic nutrients (Wear & Thurber 2015). When the
nutrient-rich water reaches the reef, it can trigger harmful algal blooms (HABs) and coral disease (The Nature Conservancy 2018) as well as reduced coral reproduction and growth, increased bleaching, and mortality. Table 3 shows the different stressors from sewage discharge and reef responses (Wear & Thurber 2015).

Recent news reports record frequent sewage breaks and spills across southeast Florida. In Fort Lauderdale from December 2019 to February 2020 over 230 million gallons of sewage leaked into the local waterways due to old infrastructure (Sainato 2020). In February 2019 parts of Miami were under “No Contact With Water” advisories after two sewage breaks in Miami Beach spilled into the Biscayne Bay (Ceballos 2022). In June 2022, “more than 1,000 gallons of raw sewage spilled into the Miami River...” (7 News WSVN 2022) leading out to the Biscayne Bay (Florida Department of Environmental Protection 2023). Then, in July 2023, millions of gallons of sewage leaked into the Intracoastal Waterway in Boynton Beach after a pipe “inside a stormwater conflict structure” burst (Sutton et al. 2023). In Miami-Dade and Broward County alone millions of gallons of sewage spills have occurred over the years due to existing pipes ranging from 50-100 years old. These outdated sewage systems are in need of replacement. Holding cities accountable through legal action and fixing the sewer systems (Miami Waterkeeper n.d.) and improving or replacing septic tanks and creating centralized facilities to regulate effluent will be significant in curbing run-off into waterways (The Nature Conservancy 2018).
Table 3 Common compounds from sewage discharge and coral reef responses.

<table>
<thead>
<tr>
<th>Stressor</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater</td>
<td>Increased coral mortality (with lowered salinity for &gt;24 h).</td>
</tr>
<tr>
<td>Dissolved inorganic nutrients (ammonium, nitrite + nitrate, and phosphate)</td>
<td>Increased coral bleaching, increased coral disease prevalence and severity, decreased coral fecundity, algal overgrowth, decreased coral skeletal integrity, decreased coral cover and biodiversity, and increased phytoplankton shading.</td>
</tr>
<tr>
<td>Endocrine disrupters (e.g., steroidal estrogens)</td>
<td>Reduction in coral egg–sperm bundles, slowed coral growth rates, coral tissue thickening.</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Source of white pox disease pathogen for corals and associated mortality, and increased pathogenicity in corals.</td>
</tr>
<tr>
<td>Solids</td>
<td>Reduced photosynthesis of coral symbionts, coral species richness, coral growth rates, coral calcification, coral cover, and coral reef accretion rates, and increased coral mortality.</td>
</tr>
<tr>
<td>Heavy metals</td>
<td>Coral mortality, coral bleaching, reduction of basic functions such as respiration and fertilization success; Fe$^{2+}$ may increase growth of coral disease.</td>
</tr>
<tr>
<td>Toxins</td>
<td>Lethal and sublethal effects on corals—highly variable and dependent on specific toxin. Reduced photosynthesis of coral symbionts, coral bleaching, coral mortality, reduced coral lipid storage, reduced coral fecundity, death of coral symbionts, and decreased coral growth.</td>
</tr>
</tbody>
</table>
7.4.4. **Local, State, and Federal Policy & Management**

In looking at the Clean Water Act (CWA), states have authority on how the act is implemented and could consider more carefully ways in which coral reefs could be considered based on their water systems. One important aspect is the Water Quality Criteria (WQC) which states, such as Florida, could adopt a more rigorous benchmark for. In fact, public input is valued in the Triennial Review of Water Quality Standards, and in 2021 Florida’s Department of Environmental Protection suggested changing the state’s turbidity WQC to alleviate stress on coral reefs. Additionally, the EPA has a Priority Pollutants list and though it is strongly under regulated when considering coral reefs, there is opportunity to address missing pollutants with known harm on corals through the National Pollutant Discharge Elimination System (NPDES) (Carlson et al. 2022).

Other important acts and programs that can be altered for coral protection include the Safe Drinking Water Act (SDWA), Federal Emergency Management Agency (FEMA)’s Flood Insurance and Restoration Programs, and Nonpoint Source Management Programs. In the SDWA laws where people and the ocean utilize the same aquifer, data and water quality can be assessed in these systems to better understand changes in reefs. Regarding FEMA and the National Flood Insurance Program, they currently incentivize people and communities to implement a green infrastructure as a flood buffer while significantly decreasing their insurance rates. However, coral reefs are not considered a green infrastructure and if listed could be beneficial both to the reef systems and the people in the community. As for nonpoint source management, it is mainly funded through incentives and in targeting coral reefs for coastal and pollution management can qualify for federal funding for greater runoff mitigation (Carlson et al. 2022).

One piece of legislation that has been updated in the efforts of protecting Florida’s coral reef is the Coral Reef Protection Act (CRPA). Originally passed in 2009, the CRPA was enacted with the goal of increasing coral protection along the coasts of all five counties bordering the FRT (Figure 1). The act is authorized under the Florida Department of Environmental Protection (DEP) and
acts as the main trustee for the reef and holds authority to assign reef protection to other government agencies across the state. Under the CRPA the DEP can also fine people that damage the reef in order to support replacing and restoring corals. As of 2020, the fines have been increased by the Florida DEP and are to be issued as follows:

- Less than or equal to 1 square meter of coral reef damage: $225 per square meter.
- More than 1 square meter and up to 10 square meters: $450 per square meter.
- More than 10 square meters: $1,500 per square meter.
- Penalties may be increased for incidents occurring within a state park or aquatic preserve, repeat violations, or for other aggravating circumstances (Florida Department of Environmental Protection 2020)

On January 10, 2023, the Florida Government updated Executive Order 23-06 which includes efforts to reduce HABs and promote more resilient communities including the Coral Reef Restoration and Recovery Initiative (Office of the Governor 2023). As of March 22, 2024, an additional $9.5 million was issued for this particular initiative to increase propagation and outplanting to promote longevity of the FRT in response to the extreme heat event over the summer of 2023 (Staff 2024). However, carbon emissions need to be cut drastically in order for coral reefs to keep up with climate change with a projected 99% reef loss under 2 degrees C warming (IPCC 2023a). In fact, GHGs need to drop by ~50% by 2030 to limit warming to 1.5 degrees C (Levin et al. 2023). Yet in 2023, the state of Florida denied joining the Carbon Reduction Program that would have provided $320 million of federal aid to the state for implementation (News Service of Florida 2023). While GHG emissions are a global problem, the U.S. is one of the top emitting countries. Florida is the 3rd largest emitting state in the U.S., and together the top 10 highest emitting states alone make up almost half the entire nation’s emissions. This combined total equates to nearly the same total emissions for the entirety of Japan, Canada, or Germany (Freidrich et al. 2021).
7.5. Discussion

To slow the rate of climate change the reduction of GHG emissions is necessary. The increasing level of CO₂ is leading to global warming which in turn is increasing sea surface temperatures and ocean acidification causing coral reef health to significantly decline. GHG reductions will need to happen concurrently with the other three actions of sufficient coral outplanting, more stringent policy and management, and updating sewage infrastructure in order to sustain coral restoration and protection. The results from Toth et al. (2023) provide reason for large restoration efforts in reefs where accretion rates are dwindling. The added coral would help reduce coastal risk until the end of the century which will be vital if GHG emissions are not reduced and climate change persists at its current rate. Southeast Florida would benefit from running carbonate budget assessment across all parts of the FRT to determine where restoration could enhance its coastline’s resiliency.

Outdated sewage infrastructure in conjunction with increased flooding has led to multiple sewage breaks and the release of harmful pollutants leaking into the coral reef ecosystem. Without local municipalities being held accountable nor placing an emphasis on updating their sewage systems it’s likely these spills will become more prevalent. While some local policy action has been implemented, it needs to be more inclusive of the various issues at play. That means improving sewage infrastructure and including GHG reductions will need to be added into local management plans. As of now, Florida has only put an emphasis on coral restoration and while important – without the other actions taking place the restoration projects won’t last long term. Community outreach and education can also be of added help in gaining support for more stringent political action and management.

Ultimately, to restore and conserve the FRT’s ecosystem services and maintain its biodiversity, it will be paramount to take action from various approaches to mitigate risks at all angles. One action cannot be successful without the other. Even if many corals are outplanted to restore the reef it will only last so long until ocean acidification hinders its growth and heat stress the corals into expelling their algae. Similarly, if Florida’s wastewater infrastructure is not replaced
then continuous spills will leave corals more susceptible to disease. And, if policy is not put in place to reduce risks across all factors, then there will be a lack of accountability and action to actually implement such mitigation tools and strategies.

8. Recommendations

Based on the analyses across all four chapters, I break down recommendations that will help promote coral reef protection to ultimately create a more climate resilient shoreline in Southeast Florida. If action isn’t taken, the FRT faces a bleak future under current climate predictions. It is paramount that greater outreach and discussions around this topic is being held amongst the different communities so more people can advocate for the reef when it comes to local, state, and federal elections and policies.

8.1. Coral Protection & Restoration

1. Perform frequent carbonate budget assessments across the entire FRT to determine restoration needs.
2. Implement sufficient coral outplanting to keep up with end of century SLR predictions to maintain ecosystem services.
3. Prioritize restoration of a variety of corals (especially those listed as threatened or endangered) to promote species diversity and enhance reef complexity.
4. Increase fines and penalties related to the Coral Reef Protection Act.
   a. Clearly mark and define coral reefs on the water & list associated fines.
   b. Increase patrolling to make sure people are being held accountable.
   c. Regulate reef associated activities to reduce possible impacts.
      i. Reduce trapping and fishing permitted on the reef.
      ii. Install mooring buoys for boat tie up to avoid anchoring into reefs.
5. Businesses and local organizations need to increase public education on how to interact with coral reefs especially in the tourist industry where people may not have had much exposure to a reef system.
   a. Design an infrastructure replacement plan to reduce contaminants from entering marine waters.
   b. Introduce water quality standards based on coral health.

8.2. Enhancing Environmental Justice
1. Strengthen workforce and opportunities for low-income communities such as increasing green jobs for even greater resiliency.
2. Upgrade local building infrastructure to be more climate resilience.
3. Assign more historic homes and buildings in low-income neighborhoods to promote preservation of local infrastructure.
4. Enhance and increase post-disaster relief for disadvantaged communities, especially for elderly folk.
5. Provide outreach, policy, educational, and preparedness materials in languages predominantly spoken amongst the different communities.
6. Incorporate EJ into local policy action.

8.3. Policy & Management
1. Globally we need to cut emissions by ~50% by 2030 to reach net-zero and limit warming to 1.5 degrees C.
2. Florida needs to participate in such GHG policy and reduction programs.
3. Increase support to local, state, and federal organizations to provide sufficient reef training and education.
4. Include coral reefs in FEMA policies.
5. Reduce pollutants that harm coral reefs by listing them on the NPDES priority pollutants list.
6. Hold municipalities accountable for sewage failure through fines and other legal action.
8.4. Discussion

Based on the conclusions I make throughout this paper; the above recommendations are the most apparent and necessary for the protection of the FRT. Greater analyses on the FRT need to be carried out in general such as carbonate budget assessments, EJ analyses, and reef policy gap analyses. While gathering more current and conclusive data can help guide further recommendations, reef stakeholders should begin work with the current research and data and adjust as necessary. It’s important to implement these recommendations now and not wait as the FRT is facing a bleak future if action isn’t taken soon. Cutting emissions to net-zero is the biggest and most effective effort the globe can make to ensure reef systems can support coastal communities through the end of the 21st century.

9. Conclusion

The overall purpose of this paper was to answer the question on how coral reefs enhance climate resilience of ecosystems and communities in Southeast Florida. Through multiple methods and analyses, I determined that the FRT has potential to significantly reduce flood risks and impacts from storm surge and SLR. Chapter 1 concluded that coral reefs can significantly reduce wave height and energy and they are more cost effective than traditional concrete breakwaters, making coral reefs an effective resilience tool amidst climate change. Chapter 2 looked closely at current impacts and future risks to the FRT. The impacts most predominantly threatening the FRT include climate change, coral diversity and disease, pollution, and direct human activity. If these impacts are not curbed, the future risks will be detrimental – likely catastrophic – to the reef.

Despite increasing attention to environmental justice nationally, little research has been done around this topic in Southeast Florida. My EJ analysis in chapter 3 chapter addressed this gap by looking at how storm surge and sea level rise are impacting disadvantaged communities in Southeast Florida and why the FRT is such an important aspect in providing protection to these communities. The FRT not only supports the local economy, but also helps protect individual
and commercial assets such as reducing impacts to home and building infrastructure. Those living directly on the coast in Southeast Florida are often more affluent and have greater accessibility to pay for storm surge damage to their property or implement more resilient structures. However, SLR threatens these homes and may lead to a greater influx of wealthy people to begin buying property at higher elevations, and thereby pushing out lower-income families out. Maintaining the health of the FRT will help support the disadvantaged communities as a form of flood protection, and policies can prevent climate gentrification. Further assessments are needed to create policy and plants that promote more equitable living.

The 4th and final chapter examined actions are needed for coral protection and restoration and determined top strategies, especially reducing CO₂ and other GHG emissions, increasing coral restoration, improving sewage infrastructure, and implementing more stringent reef policy and management. The only way to enhance and maintain restoration efforts is if substantial mitigation tools are implemented to reduce increasing risks and cut emissions to reach net zero.

Given that coral reefs support almost 25 percent of our total marine species, this delicate ecosystem is in dire need of support and protection. These reefs not only play an important role in the marine food web system, but they also provide a food resource for many people, and they reduce erosion and storm impact to coastal communities. Reefs provide jobs for fisher people and the tourism industry, allow for recreational activities, and benefit the world’s economy. An extreme rise in GHG emissions from anthropogenic activities has changed the way our oceans are functioning – a shift not seen for millions of years. This is altering food webs, species distribution and reproduction, increasing susceptibility to disease, and hindering many habitat-forming species such as corals. Ocean acidification and extreme heat are the two largest climate threats to our coral reefs and Florida is already seeing an increase in negative impacts to the FRT.
Although more research is being carried out, there is still a lack of significant coral reef assessments and analyses to determine their potential for coastal protection. The work by Ferrario et al. (2014) is the most relied upon meta-analysis for most researchers but is already 10 years old. Having only one study of its kind is insufficient; more reef analyses are urgently needed. Reefs are often regarded as being difficult to study and therefore are pushed aside when it comes to coastal restoration plans. Yet, coral reefs are the first line of defense for coastal communities when it comes to storm surge and SLR. Finally, dramatic and rapid reduction in GHG emissions is an essential action we must take to protect coral reefs and human communities, while implementing more stringent policy and greater restoration efforts.

10. References


Staff. (2024, Mar 22,). Governor Ron DeSantis announces first awards through Florida’s coral reef restoration and recovery initiative.


### Table S.1 Population and demographics of each municipality in Miami-Dade County listed from lowest in elevation (Golden Beach) to highest in elevation (Carol City).

<table>
<thead>
<tr>
<th>Neighborhood</th>
<th>Total Population</th>
<th>White alone, not Hispanic or Latino</th>
<th>Hispanic or Latino</th>
<th>Black or African American</th>
<th>Median Income (USD)</th>
<th>Poverty Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden Beach</td>
<td>548</td>
<td>56%</td>
<td>43%</td>
<td>0%</td>
<td>$250,001</td>
<td>6%</td>
</tr>
<tr>
<td>Miami Beach</td>
<td>80,017</td>
<td>35%</td>
<td>56%</td>
<td>4%</td>
<td>$65,116</td>
<td>14%</td>
</tr>
<tr>
<td>Sunny Isles Beach</td>
<td>21,996</td>
<td>47%</td>
<td>48%</td>
<td>1%</td>
<td>$57,145</td>
<td>14%</td>
</tr>
<tr>
<td>North Bay Village</td>
<td>7,884</td>
<td>25%</td>
<td>62%</td>
<td>4%</td>
<td>$76,815</td>
<td>10%</td>
</tr>
<tr>
<td>Key Biscayne</td>
<td>14,435</td>
<td>22%</td>
<td>75%</td>
<td>1%</td>
<td>$173,015</td>
<td>8%</td>
</tr>
<tr>
<td>Surfside</td>
<td>5,487</td>
<td>56%</td>
<td>37%</td>
<td>4%</td>
<td>$73,160</td>
<td>14%</td>
</tr>
<tr>
<td>Bay Harbor Islands</td>
<td>5,717</td>
<td>38%</td>
<td>55%</td>
<td>3%</td>
<td>$73,587</td>
<td>9%</td>
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<tr>
<td>Bal Harbor</td>
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<td>33%</td>
<td>0%</td>
<td>$86,172</td>
<td>21%</td>
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<tr>
<td>Indian Creek</td>
<td>82</td>
<td>61%</td>
<td>25%</td>
<td>0%</td>
<td>$100,552</td>
<td>11%</td>
</tr>
<tr>
<td>Aventura</td>
<td>38,930</td>
<td>47%</td>
<td>45%</td>
<td>2%</td>
<td>$75,211</td>
<td>12%</td>
</tr>
<tr>
<td>Miami Springs</td>
<td>13,416</td>
<td>18%</td>
<td>79%</td>
<td>2%</td>
<td>$88,196</td>
<td>12%</td>
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<tr>
<td>Sweetwater</td>
<td>19,588</td>
<td>3%</td>
<td>95%</td>
<td>3%</td>
<td>$53,159</td>
<td>16%</td>
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<tr>
<td>Virginia Gardens</td>
<td>2,419</td>
<td>21%</td>
<td>76%</td>
<td>0%</td>
<td>$75,455</td>
<td>8%</td>
</tr>
<tr>
<td>Hialeah Gardens</td>
<td>22,364</td>
<td>4%</td>
<td>96%</td>
<td>1%</td>
<td>$58,497</td>
<td>15%</td>
</tr>
<tr>
<td>Miami Lakes</td>
<td>30,830</td>
<td>8%</td>
<td>89%</td>
<td>2%</td>
<td>$90,339</td>
<td>5%</td>
</tr>
<tr>
<td>Hialeah</td>
<td>220,292</td>
<td>3%</td>
<td>95%</td>
<td>2%</td>
<td>$49,531</td>
<td>18%</td>
</tr>
<tr>
<td>Location</td>
<td>Population</td>
<td>outOf 100</td>
<td>outOf 100</td>
<td>outOf 100</td>
<td>outOf 100</td>
<td>outOf 100</td>
</tr>
<tr>
<td>-----------------------</td>
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<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Miami Gardens</td>
<td>110,497</td>
<td>2%</td>
<td>33%</td>
<td>65%</td>
<td>$56,071</td>
<td>15%</td>
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<tr>
<td>Doral</td>
<td>76,983</td>
<td>11%</td>
<td>84%</td>
<td>1%</td>
<td>$83,823</td>
<td>11%</td>
</tr>
<tr>
<td>Biscayne Park</td>
<td>3,036</td>
<td>28%</td>
<td>32%</td>
<td>34%</td>
<td>$66,382</td>
<td>17%</td>
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<tr>
<td>Cutler Bay</td>
<td>43,958</td>
<td>22%</td>
<td>64%</td>
<td>9%</td>
<td>$78,569</td>
<td>10%</td>
</tr>
<tr>
<td>Opa-Locka</td>
<td>15,888</td>
<td>3%</td>
<td>47%</td>
<td>52%</td>
<td>$30,101</td>
<td>28%</td>
</tr>
<tr>
<td>Medley</td>
<td>1,018</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
<td>$38,583</td>
<td>22%</td>
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<tr>
<td>Unincorporated County*</td>
<td>No Data</td>
<td>No Data</td>
<td>No Data</td>
<td>No Data</td>
<td>No Data</td>
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</tr>
<tr>
<td>El Portal</td>
<td>1,932</td>
<td>27%</td>
<td>35%</td>
<td>27%</td>
<td>$96,837</td>
<td>12%</td>
</tr>
<tr>
<td>West Miami</td>
<td>6,992</td>
<td>7%</td>
<td>84%</td>
<td>3%</td>
<td>$73,525</td>
<td>12%</td>
</tr>
<tr>
<td>North Miami</td>
<td>58,906</td>
<td>9%</td>
<td>32%</td>
<td>56%</td>
<td>$49,059</td>
<td>19%</td>
</tr>
<tr>
<td>North Miami Beach</td>
<td>43,023</td>
<td>17%</td>
<td>41%</td>
<td>39%</td>
<td>$56,122</td>
<td>14%</td>
</tr>
<tr>
<td>South Miami</td>
<td>11,744</td>
<td>26%</td>
<td>55%</td>
<td>10%</td>
<td>$78,830</td>
<td>13%</td>
</tr>
<tr>
<td>Pinecrest</td>
<td>17,973</td>
<td>46%</td>
<td>43%</td>
<td>2%</td>
<td>$178,095</td>
<td>7%</td>
</tr>
<tr>
<td>Miami Shores</td>
<td>11,569</td>
<td>42%</td>
<td>34%</td>
<td>17%</td>
<td>$120,833</td>
<td>7%</td>
</tr>
<tr>
<td>Miami</td>
<td>449,514</td>
<td>12%</td>
<td>72%</td>
<td>14%</td>
<td>$54,858</td>
<td>20%</td>
</tr>
<tr>
<td>Carol City**</td>
<td>64,569</td>
<td>6%</td>
<td>42%</td>
<td>50%</td>
<td>$63,454</td>
<td>17%</td>
</tr>
</tbody>
</table>
Table S.2 Total population and averages for demographics data for first 16 municipalities from low to mid elevation (Golden Beach – Hialeah) and second 15 municipalities from mid to high elevation (Miami Gardens – Carol City).

<table>
<thead>
<tr>
<th>Municipality Range</th>
<th>Sum population</th>
<th>Average White alone, not Hispanic or Latino</th>
<th>Average Hispanic or Latino</th>
<th>Average Black or African American</th>
<th>Average Median Income (USD)</th>
<th>Average Poverty Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden Beach - Hialeah</td>
<td>487,040</td>
<td>32%</td>
<td>63%</td>
<td>2%</td>
<td>$90,372</td>
<td>12%</td>
</tr>
<tr>
<td>Miami Gardens - Carol City</td>
<td>917,602</td>
<td>17%</td>
<td>53%</td>
<td>25%</td>
<td>$75,009</td>
<td>15%</td>
</tr>
</tbody>
</table>

Note for both Table S1 and S2: data collected through elevation figure 14 from Keenan et al. (2018) and census information from U.S. Census Bureau, Census Reporter, and City-Data. *Data was unavailable for the unincorporated county meaning sum and averages were based on 16 municipalities in the low to mid elevation range and 15 municipalities in the mid to high elevation range. **Figure 7 refers to Carol City as Carol Gardens likely to shorten description as it is formally known as Carol City in Miami Gardens.

Supplemental Table References


