Coral Reef Restoration in the Tropical West Atlantic Amid the COVID-19 Pandemic

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Coral Reef Restoration in the Tropical West Atlantic Amid the COVID-19 Pandemic

by

Linden Cheek

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
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Date of Approval:
November 6, 2020

Keywords: pandemic, disaster response, resilience, operational adaptation, Caribbean

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Dedication

I dedicate this thesis to coral reef restoration practitioners and all others who work tirelessly to keep this planet livable and beautiful for all creatures.
Acknowledgments

I would like to thank my advisor Dr. Maya Trotz and committee member Dr. Rebecca Zarger, for their invaluable guidance in this subject matter to which I was a newcomer. I would also like to thank Dr. James Mihelcic for his role on my committee and for his continual mentorship during my graduate career, both in person and while abroad.

This project also benefited greatly from the input of Kris-An Hinds and Michelle Platz, both of whom lent their experienced eyes and unique worldviews to improve my work. A special thanks to Mr. John Hunte from Barbados, who I have never met, but who did not hesitate to find and compile data for me, absolutely free.

Thank you to the McKenna’s for graciously dedicating a room in their house for me to work, and especially to Sue for building me a functional desk. Thank you too, to Rory, for the continual support, feedback, and encouragement, and for decorating my workspace with ocean themed chouchkies.

Finally, thank you to the coral reef restoration practitioners who took the time to complete my survey. Their responses were interesting and insightful, and this thesis would most definitely not exist without them.

This material is based on work supported by the U.S. Department of Education Graduate Assistance in Areas of National Need (GAANN) and the National Science Foundation Collaborative National Research Traineeship (NRT) award #1735320 (Strong Coasts). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the funding agencies.
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Climate change is increasing threats to coasts, both from storm surge and sea level rise.

Healthy coral reefs provide reduction in storm surges, wave energy, coastal flooding and everyday erosion, and are found across a variety of spatial scales. Given the state of coral reefs worldwide, active Coral Reef Restoration (CRR) in emerging as a necessary component of coastal protection. CRR can be classified as a nature-based solutions (NbS) for coastal protection that also provides a multitude of ecosystem-based services to both humans and other life. Nearly all literature on coral restoration efforts assume a steady-state of human-ecological interactions, but the COVID-19 pandemic of 2020 and the resulting global disruption has shown that this steady-state is not guaranteed.

This study aimed to examine CRR operations and coral reef ecosystems in the context of COVID-19 in the Tropical West Atlantic (TWA). Three research questions were posited to guide this research: 1) How is the COVID-19 pandemic directly and indirectly impacting coral reef restoration work in the TWA?; 2) How is the COVID-19 pandemic indirectly impacting the vitality of the coral reef ecosystems monitored/restored by TWA CRR programs?; and 3) How can CRR programs be resilient to future global-scale disruptions?

To answer these questions, 11 TWA CRR practitioners were surveyed on how their program and the reefs their program serve have been impacted by the COVID-19 pandemic. They were then asked to describe any operational changes their program had made or was planning to make in response to their experience with the COVID-19 pandemic. The survey was
completed online between September 3\textsuperscript{rd} and 14\textsuperscript{th} of 2020. Data on confirmed COVID-19 cases and deaths in each surveyed country/region as of September 4\textsuperscript{th}, 2020 were also collected.

Survey results showed that the COVID-19 pandemic had impacted CRR in the TWA. The most indicated causes of disruptions by CRR practitioners fell into the categories of financial lack/uncertainty, lack of reliable workforce, and inability to access field sites. These disruptions were largely driven by government protocols of stay-at-home orders and travel/boating restrictions that impeded CRR workers’ ability to perform regular work. CRR practitioners were also widely disrupted by governmental closing of borders to international travel that vastly diminished tourism and any work travel. Coral reef ecosystem health fair differently from site to site, but four respondents reported a decrease in reef fish populations and fish size. All respondents indicated either implemented or planned operational changes to their CRR program in response to COVID-19, including hiring more local workers, diversifying funding, and developing distance learning workshops. In addition, three possible partnerships between CRR practitioners and civil and environmental engineers (CEEs) were suggested, including remote monitoring of CRR sites and reframing CRR programs as NbS to coastal erosion and storm hazard.

While this thesis is a case study of the COVID-19 pandemic, its findings have implications beyond this single event. Some of the disrupting factors of this COVID-19 case study are specific to a pandemic event. However, many of the other disrupting factors - such as decreases in tourism, inability to access site(s), and financial uncertainty – are likely to occur in other major disruption events, like an economic crisis or a natural disaster. As such, many of the stated adaptation strategies, both of the CRR practitioners and those recommended for
partnership with CEEs, are important to the overall resilience of CRR programs in the face of any major disrupting event.
Chapter 1: Introduction

1.1 Introduction

Climate change is increasing threats to coasts, both from storm surge and sea level rise (Collins et al., 2019; IPCC, 2018; Storlazzi et al., 2018). Coral reefs are emerging as key nature-based solutions to coastal hazard risk reduction (Beck & Lange, 2016; Ferrario et al., 2014; Spalding et al., 2014; Storlazzi et al., 2019); they reduce storm surge, wave energy, coastal flooding, and erosion from small to large scales (Narayan et al., 2016; Spalding et al., 2014; Storlazzi et al., 2019). Additionally, the use of coral reef restoration over artificial methods of coastal protection has the vastly important advantage of providing habitat for the tens of thousands of marine species that dwell in or around coral reefs (Bayraktarov et al., 2019; Woodhead et al., 2019).

Coral reefs cover only 0.17% of the bottom area of the world’s oceans, yet an estimated 25% of all fish rely on them for at least part of their lifecycle (NOAA, 2019), they protect over 150,000 km of coastline, and shelter over 63 million people in over 100 countries, dissipating 97% of wave energy that passes over them, even in hurricane conditions (Ferrario et al., 2014; Omori, 2019; Spalding et al., 2016). The three-dimensional structure of coral reefs provides a multitude of ecosystem services (Ruangpan et al., 2019; Ruckelshaus et al., 2016; Woodhead et al., 2019), valued at up to USD 350,000 ha, which is orders of magnitude higher than tropical forests or open ocean (Albright & Cooley, 2019; de Groot et al., 2012). An analysis of the annual ecosystem services of coral reefs has valued the reefs of Puerto Rico at 1.1 billion USD/year (Brander & Van Beukering, 2013). Reefs and reef adjacent tourism based activities bring in an
estimated 7.9 billion USD to the Caribbean region and 174 million USD to southeast Florida annually (Brander & Van Beukering, 2013; Spalding et al., 2018).

Coral reef ecosystems are increasingly under threat, both from local factors and climate change impacts of ocean warming and ocean acidification. It is postulated that if global warming reaches 2ºC, more than 99% of corals will likely be lost (IPCC, 2018). Nowhere are reefs more under threat than in the Tropical West Atlantic (TWA). Since 1970, the TWA has lost between 60-80% of its reefs, impacting local populations who rely on the reefs for income, food, cultural heritage, and protection from coastal hazards (Andersson et al., 2019; Bayraktarov et al., 2016; Cramer et al., 2020).

The importance of properly managing and/or protecting coral reefs has been recognized both for their ecological importance and for their importance to human communities (Beck & Lange, 2016; Woodhead et al., 2019). As such, multiple versions of reef restoration have emerged – each with different aims and mixed results. Passive forms of restoration, such as Marine Protected Areas (MPA), have not been enough to allow reefs to recover in most cases (France, 2016). Consequently, active restoration has come to dominate the practice. Chief among the strategies used to restore reefs in the TWA is coral gardening based on the asexual propagation of corals from coral fragments grown in “nurseries” and transplanted, or “outplanted”, to degraded reefs (Reef Resilience Network, 2018). The vision being that restored corals will then spawn and propagate across wider areas of reef. Many coral gardening operations have reported encouraging successes in both coral propagation and attachment (Boström-Einarsson et al., 2020). This work restores reefs and can be used to discover particularly well-adapted coral genomes to strengthen coral populations to withstand future threats (Anthony et al., 2015; Mcleod et al., 2019). It is possible that coral gardening, along with
improved management and policy, might be able to save the reefs and better support the communities that rely on them. However, coral gardening is active restoration – meaning it relies on the active, present work of humans. These operations can suffer due to lack of funding or necessary equipment, hurricanes, and coral disease, but recent events have introduced a novel threat to coral reef restoration – the global COVID-19 pandemic.

There is much existing scholarship on the resilience of coral reefs to storms, changing climate, and even disease (Andersson et al., 2019; Hughes et al., 2018; Maxwell et al., 2019; Roff & Mumby, 2012). Over the past two decades of experimentation and observation of different “coral gardening” restoration techniques, guidelines of best-management-practices and strategies for developing coral reef restoration programs have emerged (Ford et al., 2018; Lirman & Schopmeyer, 2016; Rehr et al., 2012). Many of these best-practices consider socio-ecological links as human-ecosystems interactions are inextricable from restoration efforts (Abelson et al., 2016; Kittinger et al., 2016; Uribe-Castañeda et al., 2018; Varkey et al., 2013). However, many recommendations for restoration efforts assume a steady-state of human-ecological interactions. The COVID-19 pandemic and the resulting global disruption have shown that this steady-state of human-ecological interactions is not guaranteed. Human communities are vulnerable to disruption from a multitude of forces, both human and non-human in origin (Sarker et al., 2019).

COVID-19, officially considered a global pandemic on March 11th, 2020, has disrupted almost every aspect of human life globally (WHO, 2020). Coral reef restoration programs are no exception to this. Coral reef restoration programs have seen impacts in funding and supplies, but most importantly in disruptions to their workforce. While COVID-19 is a human disease, and therefore does not directly affect coral reef ecosystems, the disruption it causes to human systems can have many indirect effects on the coral reef ecosystems. For coral reef ecosystems
and their restoration to succeed amid future disruptions, it is imperative to understand how massive disruptions to human communities can affect CRR efforts and how restoration programs can best prepare and respond to them. As such, it is important to study and document the impact of the COVID-19 pandemic on the CRR programs in the TWA, and the types of plans CRR programs would like to institute to make their programs more resilient.

1.2 Research Goal, Research Questions and Tasks

The overall goal of this research is to understand how the COVID-19 pandemic has impacted Tropical West Atlantic coral reef restoration programs and the reefs they serve, and to identify strategies, including synergies with engineering, to build resilience to global disruptions into coral reef restoration programs. Three research questions and associated tasks guide this research.

Research Question 1 (RQ1) asks, “How is the COVID-19 pandemic directly and indirectly impacting coral reef restoration work in the Tropical West Atlantic?”

Task 1a is to discover what impacts the COVID-19 pandemic have had and are having on reef restoration operations through surveys of Tropical West Atlantic coral reef restoration practitioners.

Task 1b is to identify likely causes of these impacts through surveys of Tropical West Atlantic coral reef restoration practitioners.

Task 1c is to develop a timeline of COVID-19 in each country compiled using publicly available data and literature review.

Research Question 2 (RQ2) asks, “How is the COVID-19 human pandemic indirectly impacting the vitality of the coral reef ecosystems monitored/restored by Tropical West Atlantic coral reef restoration programs?”
Task 2a is to identify perceived changes in reef health during the COVID-19 pandemic through surveys of Tropical West Atlantic coral reef restoration practitioners.

Task 2b is to identify likely causes of changes in reef health through assessing observations and opinions of Tropical West Atlantic coral reef restoration practitioners given in the survey.

Research Question 3 (RQ3) asks, “How can coral reef restoration programs be resilient to future global-scale disruptions?”

Task 3a is to identify methods used by coral reef restoration programs to respond to the COVID-19 disruption through surveys of Tropical West Atlantic coral reef restoration practitioners.

Task 3b is to identify future methods planned by coral reef restoration programs to respond to disruptions like COVID-19 through surveys of Tropical West Atlantic coral reef restoration practitioners.

Task 3c is to compare these responses to current program resilience as assessed by respondents and major disrupting influences identified in Tasks 1b and 2b to identify likely leverage points in building increased resilience into CRR programs.

Task 3d is to identify areas where environmental engineers can assist in building resilience into CRR programs.

1.3 Organizational Overview

In this thesis, Chapter 2 explores how climate change is increasing coastal hazards, the role of coral reefs in coastal protection, and the other ecosystems services that coral reefs provide. It goes on to describe the setting of this study, namely coral reefs in the TWA and the threats these reefs – and reefs globally – are experiencing today. It then explores modern
techniques to protect and restore coral reefs, with special attention paid to the active restoration techniques of land-based (ex-situ) and sea-based (in-situ) coral gardening. It also briefly discusses sociological factors of CRR. The chapter ends with an introduction of the case-study of the COVID-19 pandemic, including discussion of the Disaster Management Cycle and definitions of resilience, including a brief discussion of restoration amid disaster.

Chapter 3 describes the research methodology, including a description of the survey used to collect the data and the method of distribution of the survey. It also explains the methodology used to collect data on COVID-19 in the countries/regions represented by each survey respondent. The chapter then details the methods of data analysis used to analyze the data collected through the survey. The chapter ends with a discussion of the safeguards put in place to ensure the ethical standards of this study were upheld.

Chapter 4 presents the results of the research and a discussion of results. The chapter is broken up into four sections, addressing RQ1, RQ2, RQ3, and the discussion, respectively. Section 4.3.2 compares the findings of Task 1b, Task 2b, and Tasks 3a and b to identify major sources of disruption to CRR operations and reef health and compare them to the adaption strategies implemented and proposed by the survey respondents. Section 4.3.3 proposes several recommended partnerships between civil and environmental engineers (CEEs) and CRR practitioners to improve the resilience of CRR programs to future widespread disruption events.

Chapter 5 summarizes findings, provides a brief discussion of the limitations of this study, and shares recommendations for future research.
Chapter 2: Background and Literature Review

2.1 Climate Change and Coastal Hazard

Nearly 40% of the global human population lives within 100 km of a coast, and that percentage is almost universally increasing as human population grows (Kapucu & Demiroz, 2017). Climate change is almost unanimously predicted to exacerbate risks for coastal communities as coastal flooding and storm intensity increase (Hinkel et al., 2014; Storlazzi et al., 2019). A growing body of evidence, however, indicates these impacts of climate change are already happening (Collins et al., 2019; IPCC, 2018; Ruangpan et al., 2019; Storlazzi et al., 2018). The damage predicted by the increased intensity of storms and floods, and sea level rise will likely be devastating, and aggravated by the degradation of natural infrastructure such as coral reefs, mangroves, and sea grasses (Beck & Lange, 2016; Collins et al., 2019; Guannel et al., 2016; Spalding et al., 2014).

Many governments are making investments to improve coastal hazard risk reduction infrastructure. The majority of these investments include artificial structures such as seawalls and breakwaters, the construction and existence of which further damages the ecosystems in which they are built (Chapman & Underwood, 2011; Ruangpan et al., 2019; Storlazzi et al., 2019). Consequently, there has been increasing interest in NbS to mitigate coastal hazard risk without the further environmental damage caused by expensive “gray infrastructure”, human engineered and constructed infrastructure (Mabon, 2019; Ruangpan et al., 2019). While still in its infancy compared to the study of NbS in other hydrogeological systems, such as wetlands, studies on coastal NbS have shown significant advantages to implementing NbS versus artificial gray
infrastructure in many locations (Beck & Lange, 2016; Elliff & Silva, 2017; Ferrario et al., 2014; Ruckelshaus et al., 2016).

2.2 Coral Reefs: Nature-based Solution to Coastal Hazard Reduction

The European Commission defines NbS as, “solutions [which] aim to help societies address a variety of environmental, social and economic challenges in sustainable ways… supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions... This implies that maintaining and enhancing natural capital is of crucial importance, as it forms the basis for solutions” (European Commission, 2020). Many other entities have similar definitions for NbS with the ultimate goal of to mitigate disaster risk, and to enhance human well-being, economic recovery, and biodiversity benefits (EESI, 2019; Bridges et al., 2018; IUCN, 2016; Lipiec, 2020).

Coral reefs are emerging as a point of interest for coastal NbS, with field measurements recording coral reefs as having the highest potential for reducing wave heights of all coastal ecosystems (Narayan et al., 2016). While only accounting for 0.17% of the area of the ocean bottom, coral reefs line over 150,000 km of coast, sheltering the communities of more than 100 million people who live along tropical and sub-tropical coasts with coral reefs (Omori, 2019). Many of these communities are found in Small Island Developing States (SIDS) and in lower-income countries. These countries are predicted to be some of the hardest hit by climate change effects, yet also have some of the least capital to respond to these effects (Briguglio, 1995; Storlazzi et al., 2018). However, healthy coral reefs are documented to provide natural mitigation of flooding and storm damage, even during higher intensity events (Roelvink, 2019; Storlazzi et al., 2019).
According to a study performed by Ferrario et al. (2014), *The effectiveness of coral reefs for coastal hazard risk reduction and adaptation*, coral reefs provide substantial protection against storm hazards, reducing wave energy by 97%, with 86% of the energy dissipating on the reef crest alone. Similarly, wave height is reduced by 84%, with 64% by the reef crest alone. The percentage of energy dissipated remains consistent even as wave energy increases from small to hurricane level waves, meaning that a healthy reef can consistently dissipate 97% of wave energy generated by even hurricane level storms. Furthermore, the dissipation of wave height by reef crests increases as wave energy increases, meaning the more powerful the wave, the more effective the reef crest is at diminishing its height (Ferrario et al., 2014). Therefore, far from being effective only in relatively calm waters, coral reefs are effective at risk reduction even in extreme storm events. However, it is not just during infrequent, high-intensity storm events that coral reefs shelter coasts. Healthy coral reefs also greatly mitigate the everyday coastal erosion caused by smaller, continuous waves (Elliff & Silva, 2017; Guannel et al., 2016; Narayan et al., 2016).

A coral reef’s ability to break waves depends on a combination of reef crest height, reef flat width, and friction with bottom roughness (rugosity), i.e. how deeply the reef is submerged, how wide it is from ocean-facing side to coastal-facing side, and the three-dimensional structure made up of the various species of corals growing in the reef (Elliff & Silva, 2017). For example, the large, branching Acropora palmata (elkhorn) and Acropora cerviconas (staghorn) corals of the TWA greatly increase both the height and roughness of the reef (Harborne et al., 2006). Unfortunately, these Caribbean species have suffered from mass die-offs in the last few decades, leaving most Caribbean reefs less able to provide protection from storm waves (Cramer et al.,
Figure 1 features a diagram of incoming waves breaking on a reef and the factors that determine wave dissipation.

![Diagram of reef zones and hydrodynamic parameters.](image)

Figure 1: Reef zones and hydrodynamic parameters involved in the process of wave height and wave energy attenuation. Reprinted from Marine Environmental Research, Vol 127, Carla I. Elliff, Iracema R. Silva, Coral reefs as the first line of defense: Shoreline protection in face of climate change, Page No. 150, Copyright (2017), with permission from Elsevier.

While data on the cost of coral reef restoration for coastal protection are limited and variable, Ferrario et al. (2014), Narayan et al. (2016), and Pascal et al. (2016) found evidence in their syntheses that coral reef restoration is less expensive or comparable to artificial storm surge protection construction. This is especially true when considering coral reefs’ ability to keep pace with sea-level rise (Temmerman et al., 2013). Additionally, when considering Caribbean nations specifically, an analysis performed by the Caribbean Catastrophe Risk Insurance Facility (2010) found that reef restoration was the most cost-effective method of coastal defense when compared to 20 other common coastal risk reduction methods, including breakwaters and adaptation methods such as new building codes and zoning laws (CCRIF, 2010; Ferrario et al., 2014).
Perhaps, though, the greatest advantage to using coral reef restoration versus artificial construction to improve coastal hazard reduction infrastructure are the simultaneous benefits that restoring healthy coral reefs can have on the human and non-human communities surrounding the restoration project.

2.3 Coral Reefs: Ecosystem Services

In 2003, the Millennium Ecosystem Assessment laid out a framework for defining and categorizing the “ecosystem services” of any given ecosystem (MEA, 2003). The concept of ecosystem services was first used in the late 1960’s and has since become an almost ubiquitous term in conversation of ecosystems and conservation. Within the assessment, ecosystem services are defined as, “the benefits people obtain from ecosystems”, a simplification of the more expansive definition establish by Costanza et al. (1997) which states, “ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life… Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions.”

2.3.1 Regulating, Provisioning, and Cultural Services

Ecosystems services can be categorized as regulating services, provisioning services, cultural services, or some combination of the three (Figure 2).

Regulating services are the benefits humans derive from the natural regulation of ecosystems processes provided by ecosystems (Reid, 2005). Protection from storm surges, flooding, and erosion, as detailed above, are some of the regulating services provided by healthy coral reefs. Coral reefs are also integral to the life cycles of around 25% of all fish species (NOAA, 2019). As such, the presence and health of coral reefs significantly regulates fish.
populations and can be considered a regulating service (NOAA, 2019). In this same thread, reefs, and the multitude of life they host, regulate the nutrients and water quality of the water column surrounding them (Woodhead et al., 2019).

Figure 2: The three types of ecosystem services provided by coral reefs and the supporting services that sustain them

Provisioning services are the goods obtained from an ecosystem (Reid, 2005). The more obvious provisioning services of coral reefs include food (both fish and shells that live within the reef and those that use the reef as feeding grounds or breeding grounds) and ornamentation
(corals, sponges, sea stars and shells used as decoration or jewelry). Coral reefs also provide fish and other animals for the aquarium trade, both for private sales and large aquarium establishments (Wabnitz et al., 2003). In some locations, especially SIDS, coral and sand are harvested from reefs to use as construction materials (Woodhead et al., 2019). The provisioning services of a coral reef include both the direct provision of these things, and the indirect provision of the money and livelihoods gained by selling these goods.

Additionally, coral reefs have a higher bio-density (species per unit of area) than any other marine environment currently known, with over 800 species of hard coral and over 4,000 species of fish identified and estimated millions of plant and animal species yet to be discovered (NOAA 2005). This biodiversity is the source of less obvious provisioning services such as an abundance of genetic resources and other technological resources (e.g. developments in biomimicry or construction techniques) (Moberg & Folke, 1999; Woodhead et al., 2019). Coral reef ecosystems are also likely hotspots for the discovery and development of new pharmaceuticals, another important provisioning service (NOAA 2005; Rehr et al. 2012).

Cultural services, while non-material, are perhaps the most indicative of what makes a specific ecosystem irreplaceable. Cultural services are the benefits humans derive through experiencing the ecosystem (Reid, 2005). The specific cultural services provided by the world’s coral reefs include spiritual services, aesthetic enjoyment, educational and scientific values, recreational services, sense-of-place, and cultural heritage, among others. Cultural services that coral reefs provide also include many of the elements marketed by reef-adjacent communities to tourists, like snorkeling, diving spots, and beaches produced by a variety of reef biological processes (Sheppard, 2014). In many human communities these cultural services also indirectly create the provisioning service of tourism income (Prideaux & Pabel, 2018; Spalding et al.,
Cultural services can be more difficult to quantify in a valuation of an ecosystem than provisioning or regulating services, especially when considering that one ecosystem likely represents distinct cultural services to different human groups. However, many methods have been developed in the past decades to give value to this hugely significant component of ecosystem worth (Brown et al., 2014).

2.3.2 Supporting Services

Supporting services are the services that, while they often do not provide direct benefit to human populations, underpin the function of all other services. The mechanisms of the supporting services of coral reefs are, to date, not well understood, although it is widely accepted that they involve the multitude of habitats provided by the three-dimensional reef structures and the biodiversity this abundance of habitat supports (Woodhead et al., 2019). Coral reefs are also integral to the creation and preservation of neighboring ecosystems, both providing protection to near-shore and coastal ecosystems and creating sand for sandy bottom pelagic habitats.

2.3.3 Coral Reefs: State, Function, and Service

Ecosystems are dynamic and complex systems defined by multiple interactions amongst various parts, including humans. In other words, an individual ecosystem service – e.g. provisioning of fish for human food – depends on the state of the rest of the ecosystem and cannot be acted upon independently. The simple logic of ecosystem services is that the ability of an ecosystem to perform a function that produces a specific ecosystem service depends upon the state of that ecosystem (Andersson et al., 2019; Elliff and Silva, 2017). Healthy ecosystems function at a higher level and are better able to provide ecosystem services. Conversely, degraded ecosystems function at a lower level and consequently are less able to provide many
ecosystem services. This is particularly important to remember when the exploitation of one ecosystem service is harmful to the overall state of the ecosystem. This phenomenon will be discussed later in Section 2.5.1.3 on overfishing on page 22.

This dependence of ecosystem services on the state of the ecosystem is a major reason the global decline of coral reefs is so alarming. As more and more reefs are degraded, the services they offer to over a billion people are becoming less dependable (Spalding et al., 2016). In many areas, this decline in the state of reef health has led to a negative feedback loop of further destruction, as humans seek out and harvest what remains of ever declining provisioning services (Spalding et al., 2016; Woodhead et al., 2019).

2.4 Study Site: Tropical West Atlantic

Nowhere do these human-reef interactions come together more clearly than in the Tropical West Atlantic (TWA). This study focuses on coral reef restoration programs in the TWA, specifically in the Caribbean countries of the Dominican Republic, Barbados, the Bahamas, Jamaica, and St. Lucia, the US territories of Puerto Rico and the US Virgin Islands, the US State of Florida, and the Caribbean coastal areas along Columbia and Belize. These countries/regions are displayed on a map of the TWA in Figure 3.

The TWA region is home to one of the most geopolitically diverse regions on earth, varying greatly in GDP, wealth, population density, political model, and culture. However, this diverse region is united in its reliance on coral reefs and the ecosystem services they provide (Andersson et al., 2019). The value of the ecosystem services provided are substantial, exemplified by the estimated USD1.09 billion/year provided in Puerto Rico alone (Brander & Van Beukering, 2013).
Reef-associated tourism is estimated to bring over US$7.9 billion dollars into the Caribbean each year, with the Dominican Republic and Puerto Rico each receiving over 500,000,000 USD in tourist spending annually. Within the Caribbean region, over 65% of reefs are used by the travel and tourism sector, and the remaining reefs, while too remote for commercializing, are almost unanimously used by local populations for fishing and fish export (Spalding et al. 2018). The coral reefs of the Florida Keys are estimated by NOAA’s Coral Reef Conservation Program to provide 5 billion USD in ecosystem services, generating 4.4 billion USD/year in local sales and supporting 70,400 jobs. The United States also generates over 100 million USD/year in revenue from coral reef fisheries (N. Miller et al., 2020). As discussed in Section 2.2 Coral Reefs: Nature Based Solution to Coastal Hazard Reduction on page 8, coral
reefs are also instrumental in providing protection from coastal hazards such as storms, flooding, and erosion (Ferrario et al., 2014; Guannel et al., 2016; Storlazzi et al., 2019).

Unfortunately, TWA reefs have been in severe decline for more than a half century. The living cover of TWA reef-building corals has declined by 50% since close monitoring began in the late 1970s, and there is emerging evidence that this decline may have begun as early as the 1950s, likely driven by increases in human population and land use changes (Cramer et al., 2020). The losses of coral in the TWA have most drastically impacted branching, reef-building hard corals like *Acropora cervicornis* (Staghorn coral) and *Acorpora palmata* Elkhorn coral (Figure 4), which used to dominate TWA reefs (Lirman & Schopmeyer, 2016). This is particularly alarming since these species’ reef-building capabilities make them integral to the reefs’ ability to keep pace with reef erosion and sea-level rise, and their large, branching frames make them especially effective at wave energy and swell reduction, and are attractive to fish and other marine species.

Figure 4: Staghorn (left) and Elkhorn (right) corals photographed at Turneffe Atolls, Belize, June 2020. Photographs by Fragments of Hope. Used with permission.
Loss of these dominant reef-builders has led to many reefs undergoing a phase-shift from coral-dominated to macro and fleshy algae-dominated ecosystems (Figure 5) (Smith et al., 2016). The majority of reef dwelling organisms rely on reef-building corals in some capacity, so their decline in favor of algae is detrimental to the entire reef ecosystem (Done, 1992; Hughes et al., 2010).

The swift decline of TWA reefs was largely the product of a synergy of natural and disease events exacerbated by human pressures (Cramer et al., 2020; Hughes et al., 2010). White band disease (Figure 6), which likely originated in the US Virgin Islands in the late 1970s, began appearing on many Staghorn and Elkhorn corals throughout the TWA in the early 1980s. This
disease, along with hurricanes and cold-water events, contributed to massive losses of up to 80% of these two major coral species (Hughes et al., 2010).

The second major reef decline event is linked to the 1983 mass-mortality of up to 90% of the sea urchin *Diadema antillarum* (Figure 7) from a still unidentified pathogen. This sea urchin is a keystone herbivore on reefs, consuming fast-growing macroalgae that compete with corals for space. While healthy reefs with high populations of herbivorous fish were not strongly affected by this event, reefs that had experienced overfishing and lacked large herbivorous fish quickly found their corals being smothered by unchecked macroalgae growth (Hughes et al., 2010; Jackson et al., 2014). These events were followed by several coral bleaching events triggered by warming seas, which have continued to reduce coral populations, leading to more phase-shifts to algae-dominated ecosystems (Cramer et al., 2020; Jackson et al., 2014).
2.5 Threats to Coral Reefs

Tropical West Atlantic reefs, like all of Earth’s coral reefs, are threatened by a combination of natural and human threats. These threats do not exist independently; they act simultaneously and often synergistically to cause stress on coral reef ecosystems. While coral reef ecosystems are naturally quite resilient, heavily stressed reefs are less likely to be able to recover from disruption events like coral disease outbreaks, bleaching, or algal blooms (Montoya-Maya et al., 2016). As discussed, the massive decline of corals in the TWA is linked to a sequence of disease and warming events, but the overwhelming scientific consensus suggests these natural disturbances have been greatly exacerbated by synergistic effects of human activities.
2.5.1 Local Threats

The greatest drivers of coral degradation are point source impacts caused by local human activities. Activities such as fishing, ship groundings or destruction of reefs for construction directly degrade or destroy reefs. Yet many other activities like sewage discharge and coastal development impact reefs in indirect but no less dangerous ways. For this section, all information is taken from Chapter 8: “Coral Reefs in the modern world” in *Biology of Coral Reefs* by Charles Shepard (2018).

2.5.1.1 Nutrients

Nutrient enrichment from sewage discharge and the runoff from terrestrial applications of fertilizer can have massively negative impacts on coral reefs, which are ecosystems that are used to nutrient poor waters. Increases in nutrients upends the balance between slow-growing calcifiers (reef-building corals) adapted to nutrient poor waters and quick-growing, nutrient loving algae. An increase in available nutrients allows algae to outcompete corals for living space on the reef structure, drastically changing the composition of reefs over time. Additionally, increases in phosphate from nutrient influx directly inhibits coral calcification by inhibiting corals’ ability to construct a skeleton. Influx of nutrients has also been linked to outbreaks of the coral predator and highly toxic crown-of-thorns starfish, plagues of which can completely consume massive swaths of corals.

2.5.1.2 Construction/Development

Coastal development can also massively impact coral reefs. Coastal dredging, often to replace sand that has been lost due to erosion caused by destruction of erosion-preventing marine ecosystems (sea grasses, mangrove, coral reefs), releases plumes of sedimentation that spread kilometers and both directly bury reefs or block light from reaching the photosynthetic
zooxanthellae corals need to survive. Inland coastal development also can release sediment plumes to similar effect. “Landfill”, the claiming of the sea to make land for human purposes, commonly destroys shallow reefs by burying them beneath concrete. In addition, the construction of sea walls and breakwaters can generate similar sediment plumes, killing nearby coral, thus damaging their ability to provide coastal protection.

2.5.1.3 Overfishing

Coral reef health is also deeply affected by local fishing. Nearly all reefs experience some amount of fishing, with an estimated 6 million people fishing on reefs around the world (Teh et al., 2013). This protein source plays an extremely key role for reef-adjacent communities, providing 50% or greater of all animal protein consumed by these communities (Sheppard et al., 2018). Reef fisheries are also important to reef-adjacent communities culturally and economically. Unfortunately, reef fisheries seem to be universally detrimental to the reefs themselves. Even subsistence fishing can cause major ecological shifts in reefs away from higher-trophic-level carnivores (sharks, grouper) to lower-trophic-level fish (Sheppard, 2014). In the modern globally connected world, many reef-adjacent communities are switching from subsistence fishing to the more profitable fishing for export. This change has dramatically increased the demand for reef fishes. As humans overfish the reefs, the reefs change in their composition of fish, with devastating trophic and ecological implications (Spalding et al., 2016).

This overfishing can happen in a variety of ways. A common form of overfishing is ‘growth fishing’, where the largest fish are taken, leaving only small fish. This means that a higher quantity of fish must be caught each time to meet the same target total catch weight. Another common form of overfishing is deemed “recruitment overfishing” and denotes the process of harvesting too many adult fish, which reduces the fish populations’ ability to replace
itself. These two types of overfishing are especially dangerous in combination because for reef fish, the larger the fish, the more eggs they produce. Egg production in reef fish is not linear, but exponential, with fully grown females producing an order of magnitude more eggs than a female half their size. As these large females are removed, the ability of the fish species to maintain its population swiftly drops. This creates a destructive feedback loop of fishers trying to meet a higher and higher demand on less and less fish with the fish less and less able to replace their population. As a result, mature fish have nearly disappeared from reefs adjacent to large human populations.

The final form of overfishing is named ‘ecosystem overfishing’ and is defined as when a certain species is fished to local extinction, leaving an ecological hole in the ecosystem with devastating implications for the reef (McWilliam et al., 2018). Overfishing is an almost universal problem for human-adjacent reefs. A study by Newton et al., (2007) found that over half of the island reef fisheries they examined were unsustainable, with an average catch 64% higher than what the reef could theoretically sustain. It is likely that these figures have only grown worse in the last decade as global human population and demand for fish has increased and the technologies developed for catching fish have become more effective, yet less selective.

2.5.1.4 Other Local Impacts

These impacts are some of the best studied threats to coral reefs, but do not even include chemical and oil pollution, heavy metal pollution, disease breakouts from human and livestock sewage, deliberate removal of reefs for development of harbors, ocean floating plastics and other trash, invasive species, direct damage of humans handling or breaking reefs, ship grounding, poisoning from anti-fouling and sunscreen, and other unknown local stressors human society places upon this ecosystem.
2.5.2 Global Factors

Local threats to reefs vary by location and are commonly the most immediate dangers to reef health. They must be addressed by the policy makers and communities that have power over their use. However, there are two major stressors driven by climate change that are global in nature and cannot be avoided by local management. These stressors are particularly dangerous in that they weaken reefs to make them more susceptible to the threats at a local level. These stressors are ocean warming and ocean acidification.

2.5.2.1 Ocean Warming

The average surface temperature of the Earth has risen by ~1°C since the 1880s due to anthropogenic climate change (Hughes et al., 2018). Today, it is commonly known that warming oceans can cause bleaching events of corals. This reality has come to the public knowledge following massive bleaching events in the Indian Ocean and along the Great Barrier Reef in 1997-1998 and again in 2001-2002, in the Caribbean in 2005, and the global and unprecedentedly long coral bleaching event of 2014-2017 (A. C. Baker et al., 2008; Beyer et al., 2018; Jackson et al., 2014; Sully et al., 2019). However, to understand why coral bleaching occurs, it is important to first understand coral biology.

What is most often called “coral” is in reality a colony of small animal organisms called polyps. Most polyps are miniscule, smaller than a pin head, with the exception of “free floating” corals, massive singular polyps that roam around the sea floor in search of food. The vast majority of reef-building hard corals are members of a symbiotic relationship with dinoflagellate algae called zooxanthellae (Figure 8). Zooxanthellae are endosymbiotic, meaning they live inside their host, and are also found in numerous other organisms including some soft corals, sea anemones, jellyfish, giant clams and sponges (Sheppard et al., 2018).
Corals and zooxanthellae have a mutualistic relationship, with both organisms relying on and benefiting each other. Corals provide zooxanthellae protection from predators, a fixed position in the light column, and enhanced access to and retention of nutrients from uptake of the coral’s excrement. Corals likewise benefit from effective autotrophy enabled by the translocation of photosynthetic products like glycerol and glucose from the photosynthetic zooxanthellae to the corals. This exchange of nutrients solves Darwin’s Paradox of how such lush ecosystems occur in nutrient deficit waters; corals and zooxanthellae exchange and recycle nutrients, achieving nutrient translocation efficiency upwards of 90% (NOAA & USDC, 2015; Sheppard, 2014). Additionally, there is also strong evidence that zooxanthellae increase coral calcification rates (see next section), although the exact mechanism for this relationship is still unknown.
(Sheppard et al., 2018). This symbiosis between corals and zooxanthellae is vital to coral health, yet it is also precarious; coral reefs often inhabit places that are only 1-2 °C below temperatures which trigger its collapse (Douglas, 2003).

“Coral bleaching” is the term given to the partial or complete expulsion of zooxanthellae from their coral hosts. Corals themselves are a combination of clear tissue and white calcium carbonate skeleton; the bright pigmentation associated with corals is actually the color of the zooxanthellae that reside within them. Corals will eject their zooxanthellae when the corals become stressed or the zooxanthellae die, leaving their white skeletons unadorned, producing the characteristic “bleached” look of these events. Bleaching can happen for a variety of reasons, including pollution, prolonged darkness like that caused by sediment clouds, and disease, but the dramatic and devastating bleaching events of modern times have been chiefly the result of heat shock. (Douglas, 2003; Sully et al., 2019) Corals can recover from bleaching if they can recruit replacement zooxanthellae quickly enough. However, if the stressed state of the corals is prolonged, the corals will die. This is damaging to reefs not just in the loss of the specific coral colony, but in that its death exposes space for colonization by, among others, macroalgae and bioeroders. Bioeroders can be especially dangerous to a reef ecosystem and the reef’s ability to provide coastal protection as bioeroders unchecked will destroy the remaining coral skeletons, reducing the reef’s three-dimensional structure (Sheppard et al., 2018). Consequently, coral bleaching can lead to damage to the reef long after the initial heat stress event.

2.5.2.2 Ocean Acidification

Earth’s oceans have absorbed approximately 40% of the $CO_2$ released by Industrial Era activities like the burning of fossil fuels and cement production (Gruber et al., 2019). While this
has kept those of us who live in the terrestrial realms of Earth from feeling the full force of this massive release of \( CO_2(g) \), earth’s oceans are chemically changing in response.

Ocean acidification is existentially dangerous to coral reefs as their calcium carbonate \((CaCO_3(s))\) skeletons are susceptible to dissolution with decrease in pH. Corals produce \( CaCO_3(s) \) in the form of aragonite to form their skeletons and need an aragonite saturation state \((\Omega_{arag})\) of at least 3.3 with a preferred \(\Omega_{arag}\) of 4 or more (Sheppard et al., 2018). The aragonite saturation state is calculated by finding the product of the concentrations of calcium [\(Ca^{2+}\)] and carbonate [\(CO_3^{2-}\)] ions at the temperature, salinity, and pressure of in situ conditions, divided by the equilibrium constant for aragonite under those conditions \(K_{arag}\):

\[
\Omega_{arag} = [Ca^{2+}] [CO_3^{2-}] / K_{arag} \quad \text{equation 1}
\]

Clearly, for corals to have the aragonite they need to secrete their skeletons, the foundation of coral reefs, they need sufficient levels of dissolved calcium and carbonate. Unfortunately, as the amount of \(CO_2\) released into the atmosphere – and thereby dissolved into the oceans – increases, the amount of available carbonate decreases. Equations 2-5 summarize the equilibrium equations of dissolution/precipitation of calcium carbonate in seawater as influenced by dissolved carbon dioxide, \(CO_2(aq)\) and carbonate, \(CO_3^{2-}\).

\[
CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \quad \text{equation 2}
\]

\[
H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad \text{equation 3}
\]

\[
HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \quad \text{equation 4}
\]

\[
CaCO_3(s) \leftrightarrow Ca^{2+} + CO_3^{2-} \quad \text{equation 5}
\]
It might appear from these equations that an increase in dissolved carbon dioxide would drive levels of carbonate up, causing more calcium carbonate to precipitate according to equation 5. The equilibrium reactions, however, result in the formation of more bicarbonate, $\text{HCO}_3^-$, and the dissolution of solid calcium carbonate. This phenomenon is well studied and documented (Cotovicz et al., 2020).

Before the industrial revolution, average carbonate species proportions in tropical seawater were 88% bicarbonate, 11% carbonate, and 1% carbonic acid, conditions that allowed for reef growth. Today the proportions are 90% bicarbonate and 9% carbonate with conditions of 93% bicarbonate and 7% carbonate predicted for later this century. These ratios, while not unheard of in the past millennium, are changing much too swiftly for natural buffering mechanisms to take place or for corals to be able to adapt (Sheppard et al., 2018). The TWA’s Caribbean basin is one of the areas most affected by ocean acidification, with one of the fastest changing chemical environments in the world. Some areas within the TWA have seen drops in $\Omega_{\text{arag}}$ in excess of 40% (Andersson et al., 2019). As $\Omega_{\text{arag}}$ drops, the rate at which corals lay down new layers of skeleton decreases.

Reef growth is naturally in a constant tug-of-war between building efforts and eroding efforts. The growth of reefs largely depends on reef-building corals depositing aragonite and the cementation of this porous aragonite with the addition of fine sediment. The simultaneous erosion of reefs is due to a myriad of causes, from animal causes like burrowing or coral eating worms and foraging parrotfish, to storm damage, to rasping of sand particles. Additionally, the aragonite of reefs is alkaline and can dissolve in acidic seawater (Sheppard et al., 2018). Net reef growth, vital for the reef ecosystem’s ability to keep up with sea level rise and serve as coastal protection, is dependent on corals producing new aragonite faster than the old deposits can be
eroded away. As seawater pH changes and less carbonate is available for deposition, this growth equation moves into the negative and reefs begin eroding away.

Lower seawater concentrations of carbonate have also been shown to reduce the strength of what aragonite deposits corals do make (Mollica et al., 2018). Consequently, coral reefs experiencing ocean acidification are much less likely to recover from damage caused by storms, bleaching, or other threats (Albright & Cooley, 2019; Pendleton et al., 2016). This, along with ocean warming has caused the Intergovernmental Panel on Climate Change to predict a mortality of >99%, i.e. functional extinction, of reef building corals if global warming is not kept below 2°C (IPCC, 2018).

2.5.3 Natural Factors

Like all ecosystems, coral reefs have faced threats as long as they have been in existence. These threats include but are not limited to predation, storm damage, naturally caused changes in pH, salinity, temperature, and sea level change. As discussed previously, these natural factors can all be exacerbated, and sometimes indirectly caused, by human activity. Another natural factor that effects the resilience of TWA reefs is their geological context. There is significant evidence that TWA reefs are less resilient than Indo-Pacific reefs. The main reasons for this seem to be an abundance of microalgae in the TWA and notably more biodiversity in Indo-Pacific reefs (Roff & Mumby, 2012).

These differences are thought to be the result of major tectonic, geological and climate events, specifically the closing Tethys Sea that used to connect the Indo-Pacific ocean to the Western Atlantic around 5.2 million years ago and the emergence of the Isthmus of Panama around 3 million years ago (J. B. C. Jackson & O’Dea, 2013). This physical separation led the two bodies of water to diverge along different evolutionary paths. It is suggested that the TWA
was more biodiverse at one point, but glaciation during the Pliocene/Pleistocene caused many coral reef species to go extinct. Today, the Indo-Pacific region has at least 10 times more fish and coral species than the TWA, and no reef building corals in common (Sheppard et al., 2018). This lack of biodiversity is not problematic in itself but does make TWA reef ecosystems more vulnerable because there is less functional redundancy, defined as multiple species sharing similar arrays of traits and able to fill the same ecological niche (Andersson et al., 2019; McWilliam et al., 2018). A striking example of this vulnerability in action is found in the *Acropora* genus of coral. The TWA has only three species of *Acropora* reef-building hard corals, the two dominant species of which, Elkhorn (*Acropora palmata*) and Staghorn (*Acropora cervicornis*), saw massive declines in the 1980s due to White Band disease and other compounding factors (see Section 2.5.3 Natural Factors on pg 29). This absolutely devastated many TWA reefs since there was no functionally redundant species of coral to fill their ecological niche. In contrast, the Indo-Pacific has over 100 species of *Acropora* and extensive functional redundancy (Sheppard et al., 2018).

Imminently important to both humans and non-humans, TWA reefs are under threat from local and global human impacts. TWA reefs are also less able to respond with resilience to the myriad of stressors placed on them than their Indo-Pacific counterparts (McWilliam et al., 2018; Roff & Mumby, 2012). The loss of coral reefs locally reduces food security, destroys livelihoods, and exposes communities to hazard. The loss of reefs globally could collapse oceanic ecosystems far beyond the reefs themselves. Considering these truths, humans have realized the need for decisive action to foster the conservation and restoration of coral reefs.
2.6 Reef Restoration Techniques

2.6.1 Defining Restoration

Restoration is defined by the Society for Ecological Restoration International Science & Policy Working Group as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed... restoration attempts to return an ecosystem to its historic trajectory” (Boström-Einarsson et al., 2020; SER, 2004). The ecological goal of restoration is to reintroduce or “restore” the biotic and abiotic elements necessary for an ecosystem to continue on its historic trajectory. However, an implied goal of restoration is often that of restoring an ecosystem to a state where it can continue producing ecosystem services valued by humans. Restoration comes in many forms, but most can be sorted into either passive restoration (i.e. rehabilitation, natural regeneration, indirect restoration) or active restoration (direct restoration), though many operations employ a combination of these techniques (Aronson et al., 2016; Boström-Einarsson et al., 2020; France, 2016). It is also important to note, as Sheppard (2014) states in the book *Coral Reefs: A Very Short Introduction*, that when humans talk about restoration, we must remember that we cannot manage ecosystems; we can only manage how humans interact with ecosystems.

2.6.2 Passive Restoration

Passive restoration aims to indirectly improve the ecological state of an ecosystem by removing degradation agents, changing infrastructure, creating regulations or placing protections over an ecosystem and then relying on its remaining natural capital to naturally restore the ecosystem to a healthy state (Boström-Einarsson et al., 2020; Precht, 2006). The chief example of passive restoration in coral reef ecosystems is the Marine Protected Area (MPA). MPAs, the marine equivalent of national parks, reduce or disallow certain human activities, like fishing and...
the removal of natural resources (Abelson et al. 2016). However, apart from a few exceptions, MPAs on their own have been unable to prevent further biodiversity declines, and the rate of recovery they allow are too slow to reverse past degradation (France, 2016). For this reason, most restoration operations are strengthening passive restoration initiatives with active restoration techniques.

2.6.3 Active Restoration

Active restoration, in contrast to passive restoration, involves the direct intervention by humans in an ecosystem. Examples of active restoration interventions are “substratum amendment, exotics control, habitat conditioning, and reintroductions” (Gann et al., 2019). All of these methods of restoration have been used in coral reef restoration and are described next.

2.6.3.1 Artificial Reefs, Substratum Alteration and Substratum Stabilization

Historically, the major focus of reef restoration was the creation of artificial reefs or reef augmentations. These restoration initiatives involve the artificial creation or alteration of the reef structure itself to create artificial “reef” for corals to affix themselves to, including all objects that are placed on the seabed to serve as a reef and all objects that are used to expand or stabilize the reef. While some rely on natural recruitment, restoration projects such of these are commonly paired with direct transplantation or outplanting of corals from nurseries (see next sections) (Boström-Einarsson et al., 2020). The major advantage of artificial reef creation is the relatively expedient replacement of a reef structure that would take centuries to reform naturally. However, this style of restoration has the significant disadvantage of being highly technical and expensive, with complicated logistical and legal matters that often cause them to not be completed until years after the initial degradation/destruction event (Lirman & Schopmeyer, 2016; Precht, 2006).
A recent development in artificial reef restoration is the use of 3D printing. 3D printing has been used in at least seven different projects to date, including larva-containing “seeding units” that self-attach to reef structures, seabed-placed high-surface-area terracotta tiles that provide structure for reattachments and safeguard against sedimentation, calcium-carbonate cylinders for polyp recruitment, giant concrete structures that mimic entire reef sections, and even the experimental “bioprinting” of coral replicas made of polymer gels and hydrogels (Folk, 2020).

While these innovations are important additions to the coral reef restoration toolbox and technological advancement is making them more cost-effective, the major trend in reef restoration in the TWA is away from structural augmentation and towards a focus on direct propagation and transplantation of the corals themselves (Lirman & Schopmeyer, 2016).

2.6.3.2 Direct Transplantation

The first developed and most studied method of active restoration is “direct transplantation” which denotes the practice of taking coral fragments from a donor reef and affixing them to a recipient reef. The coral fragments used for direct transplantation are often coral fragments salvaged after a damaging storm event or from places where human construction will soon destroy or disturb existing colonies. In some case, coral fragments are harvested in minimally damaging numbers from healthy reefs, especially if these reefs show resistance to stress, indicating a genome that might better withstand conditions altered by climate change. However, continual harvesting can negatively affect the donor reef, and direct transplantation is viable only with fast growing coral species (Boström-Einarsson et al., 2020).
2.6.3.3 *Asexual Coral Propagation, Coral Gardening*

As the need for coral transplants outgrew the rate that restoration workers could sustainably harvest fragments from donor reefs, a more sustainable method of producing coral transplants was invented; coral gardening (Boström-Einarsson et al., 2020).

Pioneered by Rinkevich (1995), coral gardening adds a “nursery stage” to the direct transplantation method. Coral gardeners initially collect donor fragments from healthy reefs in the same manner as direct transplantation, but instead of immediate outplanting, the fragments then undergo a stage of mariculture in coral “nursery” sites, protecting growing corals at their most vulnerable stages. While in these nursery sites, coral polyps within the fragments asexually propagate, cloning themselves to grow into larger, viable corals which are then either outplanted onto degraded reefs or fragmented more to create the next generation of donor corals (Boström-Einarsson et al., 2020; Lirman & Schopmeyer, 2016; Precht, 2006). Following this cycle, a small initial donor group of corals can be propagated repeatedly to create enough outplants to repopulate an entire reef. Based on this simple method, the practice of coral gardening has swiftly developed in the past decades to where coral gardening has become the most widely adopted form of restoration in the TWA, with 10,000’s of corals being outplanted by TWA CRR practitioners annually (Lirman & Schopmeyer, 2016). Due to this prevalence, coral reef restoration programs that employ coral gardening as their chief restoration method will be the focus of the remainder of this study.

Corals can either be grown in-situ (sea-based) nurseries in protected areas accessible to coral gardeners, or ex-situ (land-based) nurseries where corals are reared in closely monitored flowing-water tanks. Ex-situ nurseries (Figure 9) have the advantages of being easily accessed by gardeners and the ability to closely control the environment of the growing corals. Ex-situ
systems are separate from the ocean ecosystems and have environmental controls, so the growing conditions for the corals can be kept stable and free of storm events, pollution, predators, competitors, disease spread and temperature fluctuations. Ex-situ gardens also lend themselves to lab work, as coral samples can be easily harvested and be used for lab experiments or gene banking on-site. Ex-situ nurseries are most commonly used for sexual propagation of corals, since their controlled environment enables them to propagate corals from larvae, although some also practice asexual propagation of fragments from donor corals. Despite these benefits, ex-situ systems remain less common than their in-situ counterparts, largely due to them being significantly more expensive, requiring a much higher level of technology, and requiring a much higher level of training for the coral gardeners (Reef Resilience Network, 2020).

Figure 9: Inexpensive land based (ex-situ) nursery at Boy Scouts STEM education program. Used with permission from Plant a Million Corals.
In-situ coral nurseries are generally established in a location that is relatively sheltered, minimally influenced by humans (e.g. in an MPA) yet accessible to personnel, with appropriate abiotic conditions and bottom type for corals to thrive. However, beyond these characteristics, in-situ coral nurseries are almost as diverse as they are numerous. There is no one-size-fits-all approach to coral gardening, and each program – and often sites within one program – will adjust their methodology to meet their specific context. Coral fragments can be grown on either floating or fixed apparatus.

Floating nurseries, also known as mid-water nurseries, suspend coral fragments on lines, frames, or “tree” structures anchored to the seabed and suspended in the water column using subsurface floats. The benefits of using a floating system are that they can decrease disease, sedimentation danger, predation, and competition and increase coral growth rates. Floating nurseries can also be lowered or raised within the water column to help the corals survive storms or temperature fluctuations. The drawbacks to using a floating system include the need for frequent monitoring and maintenance as coral and algal growth can cause the structures to sink. It is also not recommended to use floating nurseries in areas with frequent boat traffic unless the water column is deep enough to ensure the avoidance of collisions and entanglement. Floating nursery structures must also be designed to reduce the possibility of entanglement of marine life, such as sea turtles and fish. Finally, floating nurseries are usually only feasible in somewhat deep water, meaning the nursery site might be more difficult for gardeners to access, usually necessitating access to a boat, increasing cost of operations (Reef Resilience Network, 2018).

Fixed, or fixed-to-bottom, nurseries can be broken into two main categories: block and frame. Block nurseries denote the attachment of coral fragments to concrete slabs, cinder block, or similar substrate. Block nurseries can be the best choice for shallow water nurseries or areas
with heavy boat, swimmer, or marine life traffic, where floating apparatus is not an option. Frame nurseries are made of metal, plastic mesh, or PVC frames anchored to the seabed, with coral fragments attached to the mesh/frame. The benefits of using a fixed nursery structure include the ability to be used in shallow or heavy traffic areas, the lower potential as a hazard to marine life, the hardiness and longevity of the structures, and ability to provide immediate habitat to reef fish and invertebrates. The drawbacks of a fixed system include lower coral growth rates than floating systems, microalgae accumulation, higher rates of predation and competition for space for the corals, and high maintenance needs, largely to counteract the other drawbacks. Both fixed and floating in-situ nurseries require maintenance, most commonly including removal of coral predators (damselfish, snails, and fireworms etc.), repair and replacement of nursery structures, and removal of diseased coral fragments (Reef Resilience Network, 2018).

Once the coral reaches a determined size-threshold, it is either re-fragmented to asexually propagate more coral fragments to be re-“planted” in the nursery or outplanted onto a degraded reef. “Outplanting” is the name given to the process of transferring coral fragments from coral nurseries to affix it on a chosen degraded reef. The goal of outplanting is to “reseed” degraded reefs with healthy and sexually mature corals to assist in natural reproduction and population recovery of the reef’s coral. Outplanting also has the immediate benefits of increasing the complexity of the reefs’ three-dimensional footprint, creating habitat space for other reef lifeforms. It is the survival of these transplants or “outplants” that measures the success of a CRR program (Reef Resilience Network, 2018).
Table 1: Comparison of field-based coral nursery types. Based off data from Reef Resilience Network (2018)

<table>
<thead>
<tr>
<th>Nursery Type Characteristic</th>
<th>Floating</th>
<th>Block</th>
<th>Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of vertical space</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Predation</td>
<td>Less</td>
<td>More</td>
<td>More</td>
</tr>
<tr>
<td>Water flow/circulation</td>
<td>More</td>
<td>Less</td>
<td>Less</td>
</tr>
<tr>
<td>Able to raise/lower</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Coral growth rates</td>
<td>Higher</td>
<td>Lower</td>
<td>Lower</td>
</tr>
<tr>
<td>Macroalgae accumulation</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Less</td>
<td>More</td>
<td>More</td>
</tr>
<tr>
<td>Hazard to marine life</td>
<td>More</td>
<td>Less</td>
<td>Less</td>
</tr>
<tr>
<td>Suitable for shallow areas</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Long lasting</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Provides habitat for reef life</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Inexpensive/ easy to construct</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

A more recent addition to the coral gardening toolbox is *micro-fragmenting*. The previous techniques mentioned are used almost exclusively with fast growing “weedy” corals such as branching *Acropora* corals. Despite their ecological importance and resilience to climate
change, massive corals were largely ignored because their slow growth and thick skeletons makes asexual propagation through fragmentation challenging. Micro-fragmenting makes the asexual propagation of massive corals much more feasible. Developed by Dr. David Vaughan of Mote Marine Laboratory in 2013, micro-fragmenting denoted the process of creating \(~1\,cm^2\) fragments that are then grown to \(~6\,cm^2\) before outplanting (Figure 10). This procedure was able to achieve growth rates 10 times faster than traditional large fragmentation. These fragments can then be assembled around a large area of dead framework where they will then grow together, knitting a continuous cover over previously dead reef (Page et al., 2018). Most recently, groups like Fragments of Hope in Belize have harvested corals from the wild, micro-fragmented, and directly outplanted to degraded reefs (Carne, 2020).

![Figure 10: Outplants of microfragments of same genotype coral in 2014 (left) and same fragments fused into one coral colony in 2016 (right) Coral head has since spawned in 2020, 50 years faster than what would occur naturally. Used with permission from Plant a Million Corals.](image)

Which method or methods of restoration are chosen for a site often depends not just on the environmental conditions of the sites, but also on the locally available materials. Regardless
of the approach, coral gardening is growing in the TWA, with tens of thousands of corals being outplanted onto degraded reefs each year (Lirman & Schopmeyer, 2016). Studies to date on coral gardening report encouraging survivorship rates of outplants; 66% compared to the terrestrial ecological restoration rate of 50% or lower (Boström-Einarsson et al., 2020).

Beyond species recovery and reef restoration, in-situ coral gardening also has the potential of providing livelihoods to local stakeholders within reef-adjacent communities, both as coral gardeners and through restoration based eco-tourism. This can create community buy-in to the restoration program, as well as give local stakeholders alternative income opportunities besides fishing and other activities that can further damage the reefs. Coral gardening programs can also easily include educational and outreach programs and lend themselves to work with “citizen scientists.” Finally, coral nurseries and outplanting sites can also serve as “living laboratories” to make important scientific inquiries into coral and reef resilience and ecology (Lirman & Schopmeyer, 2016).

2.6.4 Socio-Ecological Aspects of Restoration

It is important to remember in any discussion of restoration work that, as Baker & Eckerberg (2013) stated, restoration is “best seen not only as a technical task but as a social and political project.” Restoration happens not only within an ecological context, but also within a complex and dynamic cultural, political and economic context (France, 2016). The sociological aspects of coral reef restoration have long been recognized as important and are much studied, including the development of multiple frameworks to analyze and leverage these dynamics (Fidelman et al., 2014; Rehr et al., 2012; Varkey et al., 2013). One aspect of the sociological dynamics of restoration that has not been explored much, however, is how the massive disruption
of human societies globally impacted reef restoration. This scenario has become a reality with the COVID-19 pandemic.

2.7 COVID-19, Disaster and Resilience

2.7.1 COVID-19: Appearance and Spread

Coronavirus disease 2019, known colloquially as COVID-19, is an infectious disease caused by sever acute respiratory syndrome coronavirus 2 virus (SARS-CoV-2). COVID-19 was first identified in Wuhan, Hubei, China in December 2019, giving the disease its “2019” moniker, although it did not reach pandemic level until 3 months into 2020.

The first case of COVID-19 is believed to have occurred in Wuhan in November 2019. It is believed to have animal (zoonotic) origin, possibly from bats or pangolins (WHO, 2020). Human-to-human transmission of COVID-19 was confirmed by a study in China on January 20th, 2020 and announced by the WHO on January 21st (Li et al., 2020). Within the first three months of COVID-19 infecting a human, over 1 million people were infected and 50,000 died (NIH 2020).

COVID-19 is not the only coronavirus to affect humans. Four human coronavirus strains, NL-63, 229E, HKU1, and OC43 are linked to minor illnesses, but two, SARS-CoV, and MERS-CoV, in addition to SARS-CoV-2 (COVID-19) can lead to serious illness and death (NIH 2020). SARS-CoV and MERS-CoV, known colloquially as SARS and MERS, both caused epidemics. The disease known as SARS was first identified in Asia in February 2003. It quickly spread to over two dozen countries around the world but was contained in under four months. 8,098 people contracted the disease, and 774 died. Middle East respiratory syndrome (MERS), was first identified in Saudi Arabia in 2012 and spread to 27 countries, though the total
confirmed cases has not risen much above 2,500 and nearly 80% of these cases were in Saudi Arabia (NIH, 2020).

COVID-19 is spread through respiratory particles, most commonly transmitted through coughing or sneezing, but that also are produced by talking, singing, and laughing. Troublingly, around 40% of people who contract the virus can spread it without ever showing symptoms themselves (NIH 2020). This discovery led to the WHO recommendation of “social distancing” of at least 1 meter between persons, and the United States’ CDC recommendation of social distancing of 2 meters (6 feet) (CDC 2020; WHO 2020). This recommendation, along with alarming rates of spread of the virus, led many governments to release curfews, stay-at-home orders, and cessation of all but “essential” business, along with the closing of borders. This research seeks to explore what effect these disruptions have had on coral reef restoration programs and the reefs they serve.

2.7.2 Disaster Management Cycle and Resilience Cycle

Humans and human societies experience many varieties of disasters beyond pandemics. While disasters are usually colloquially divided into human-caused disasters (e.g. war, economic recessions, nuclear reactor meltdowns) and natural disasters (e.g. hurricanes, tornados, landslides, drought), in the modern world this boundary is not often distinct, as is exampled by the massive death toll of non-whites in the 1928 Okeechobee hurricane, war-induced famine, climate-change aggravated tropical storms and wildfires, and even the zoonotic-human interactions that led to the COVID-19 pandemic (IPCC, 2018; Johnson et al., 2020; Pfost, 2003). The quest to understand this interaction between human action and disaster risk has birthed extensive disaster management literature on how disasters happen, how they impact human communities/systems, and how human communities/systems attempt to become resilient to
Disasters can be defined as an “accident or natural catastrophe that causes great damage and loss of lives” (Moore & Lakha, 2006). One of the most common frameworks used to describe and analyze disasters is the disaster management cycle (DMC) (Sawalha, 2020). The traditional DMC includes stages of mitigation, preparedness, disaster event, response, and recovery that then cycle into mitigation of the next disaster (Figure 11). Mitigation and preparedness can be combined into one category: mitigation, denoting all actions taken to mitigate damage from a future disaster. Response denotes all human and institutional response immediately after the disaster event. Recovery denotes the long-term actions taken to recover from the damage of the disaster (Beach 2019).

Tangential to the study of disaster management is the study of resilience. Many definitions of resilience can be found in resilience literature, but these definitions generally describe the ability or “capacity” to reduce or withstand shocks and stresses while maintaining core functions (Clark-Ginsberg et al., 2020; Manyena et al., 2019). According to Manyena et al. 2019, resilience consists of five main capacities: preventative, anticipative, absorptive, adaptive, and transformative. These capacities correspond to stages of the DMC: anticipative and preventative resilience capacities perform during the mitigation and preparedness stage, absorptive capacities perform during the response stage, adaptive capacities perform in the short-term during the response stage and in the long-term during the recovery stage, transformative capacities perform during the recovery and mitigation stages.
2.7.3 Disaster, Resilience, and Restoration

Given the widely recognized importance of coral reefs in mitigating coastal disaster impacts combined with the literature supported necessity of active restoration to maintain this mitigation ability, it follows that sustained operation of coral reef restoration programs is integral to coastal resilience in reef adjacent communities. It is therefore important to study how reef restoration programs themselves are impacted by disasters. Although there is much scholarship on the resilience of coral reefs to various disasters (Marcum et al., 2017; Steneck et al., 2019; Yender & Michel, 2010), on the resilience of human communities to coastal hazard driven disaster (Hallegatte et al., 2013; Varda, 2017), and on how coral reefs contribute to this human resilience (Beck & Lange, 2016; Temmerman et al., 2013; Van Zanten et al., 2014), and even how disaster response can empower human communities to invest in NbS (Lin, 2019), there is extremely limited scholarship regarding how coral reef restoration is impacted by disaster. An example of this gap can be found in scholarship of the impact of hurricanes.
Hurricanes are a common cause of disaster in coastal areas. Climate science indicates that hurricanes will likely increase in strength due to the effects of climate change (Collins et al., 2019). There is extensive literature on how hurricanes impact both human communities (Marcum et al., 2017; Pfost, 2003; Takasaki, 2017) and coral communities (Gardner et al., 2005; Steneck et al., 2019; Wells et al., 2010; Woodley et al., 1981). There is also extensive literature on how healthy coral reefs can help protect humans from hurricane damage (Ferrario et al., 2014; Ruangpan et al., 2019; Van Zanten et al., 2014). However, there is limited literature on how coral reef restoration programs themselves are impacted by hurricanes. One study provides recommendations on where to focus CRR initiatives in light of hurricane patterns (Beyer et al., 2018). Another study addresses the implications of increased local and global stressors on coral reefs, including hurricanes, for CRR managers, but focuses solely on management strategies to increase the ecological resilience of the coral reefs without considering the resilience of the restoration programs themselves (Anthony et al., 2015).

This phenomena also holds true in the larger body of restoration/conservation scholarship, with the slight exception of studies performed on the impact of war on conservation initiatives within the continent of Africa (Kinzig & McShane, 2015; D. C. Miller et al., 2015; Ordway, 2015). Existing scholarship leaves the question of, how ecological restoration programs are impacted by disaster, not just in terms of the disaster’s impact on their restoration subject (i.e. the coral reef), but on the program’s ability to operate, largely unexamined.

Resilience building, like mitigation, begins by understanding risk and risk drivers; similarly, resilience cannot be understood without reference to vulnerability (DFID, 2011; Manyena et al., 2019). The COVID-19 pandemic presents a unique and novel opportunity to assess the vulnerabilities and resilience of CRR programs to the hazard of global pandemics and
similar disruptions to human systems. This study seeks to identify vulnerabilities and resilience capacities of TWA coral reef restoration programs in reference to the COVID-19 pandemic. There will be specific attention paid to adaptive and transformative capacities that have come out of this novel global event. This topic is especially important given the ever-increasing likelihood of similar global disruptions in the near future and the importance of reversing coral reef degradation (Collins et al., 2019; K. F. Smith et al., 2014).
Chapter 3: Materials and Methods

This chapter presents the materials and methods used to accomplish Tasks 1a, 1b for Research Question 1 (RQ1), Tasks 2a, and 2b for Research Question 2 (RQ2), and Tasks 3a, 3b, and 3c for Research Question 3 (RQ3).

3.1 Survey of TWA CRR Practitioners

On September 3rd, 2020, emails containing links to an electronic survey were distributed to 14 CRR practitioners in the TWA. The criteria established for those eligible to participate in the study were 1) 18 years or older of age, 2) current employee/practitioner at a CRR program in the TWA, and 3) been employed by this CRR program for one year or more. The third criterium was added to help ensure the respondent had enough experience with their restoration program to be able to identify changes in operation from pre-COVID-19 to amid COVID-19 conditions. Purposive and chain-referral, i.e. “snowball”, sampling was used to target CRR practitioners in the TWA. The original sampling was purposive in that the original list was compiled of TWA CRR practitioners known by Dr. Maya Trotz, chief adviser to this study. The reminder of the sampling was through chain-referral as each invitation email also asked the recipients to forward the invitation email to any others within their organization who met the study criteria. The survey followed accepted social science research methods and techniques. (Kittinger et al., 2016; Russell, 2006) The survey included both multiple choice and open-answer questions, designed to record specific details desired by the PI while allowing the respondents to address what aspects of CRR amid COVID-19 seemed most important to them. A list of survey questions can be found in Appendix B.
The survey was distributed by sending each CRR practitioner from the purposive sampling an email containing a brief introduction to the study, including an explanation the purpose of the study and their role within the study should they choose to participate. (Appendix C) The survey was then accessed through a link in the invitation email. The link led to an online survey hosted through Qualtrics, an online survey platform. The survey opened with a consent page following the USF IRB format (Appendix B). The participants were again informed of the purpose of the study and their role in it if they chose to accept. Their consent was given by choosing to continue with and submit the survey.

3.1.1 Research Question 1 (RQ1): Task 1a, 1b, and 1c

To answer RQ1, Task s1a, 1b, and 1c were employed. Task 1a surveyed TWA CRR practitioners to discover what impacts the COVID-19 pandemic has had and is having on reef restoration operations. Task 1b surveyed TWA CRR practitioners to identify likely causes of these impacts. Task 1c used publicly available data and literature review to develop a timeline of COVID-19 in each country studied (see section 3.2).

The topics covered in the survey to address Task 1a and 1b were 1) how the COVID-19 pandemic has impacted the respondent’s ability to work, the operations of their program, and the community(s) their program serves and 2) what were the main causes of disruptions to the CRR program. A key subset of the questions asked to address these topics includes, “Since COVID-19 began impacting the reef restoration program you work for, has your program experienced disruption to any of the following?” and “Please select which of the following, if any, have made it difficult for you and the other workers at your program to maintain regular restoration work during the COVID-19 pandemic.” These questions and the full list of possible answers can be found in Appendix B.
3.1.2 Research Question 2 (RQ2): Task 2a and 2b

Results from Tasks 2a and 2b are used to answer RQ2. Task 2a surveyed TWA CRR practitioners to identify changes in reef health during COVID-19 pandemic. Task 2b surveyed TWA CRR practitioners to identify likely causes of changes in reef health.

The survey used to address RQ1 (see section 3.1.1) was also used for RQ2. The topics covered in the survey to address Tasks 2a and 2b were 1) the changes in the reef sites were noticed by the respondents during the COVID-19 pandemic, and 2) the changes in the human-reef interactions noticed by the respondents during the COVID-19 pandemic. A key subset of the questions related to these topics include, “If you have noticed any change(s) in the human use/interaction with your reef restoration site(s) since COVID-19 began to impact the community... please describe the change(s) below,” and, “If you have noticed any change(s) in the coral reef ecosystem of your reef restoration site(s) since COVID-19 began to impact the community... please describe the change(s) below.” These questions and the full list of possible answers can be found in Appendix B.

3.1.3 Research Question 3 (RQ3): Task 3a, 3b, 3c and 3d

To answer RQ3, Tasks 3a, 3b, 3c, and 3d were established. Task 3a surveyed TWA CRR practitioners to identify methods used by their CRR programs to respond to COVID-19 disruptions. Task 3b surveyed TWA CRR practitioners to identify methods planned by CRR programs to respond to COVID-19 disruption. Task 3c surveyed TWA CRR practitioners to compare these responses to hotspots identified in Tasks 1b and 2b, and to identify likely leverage points in building increased resilience into CRR programs. Task 3d identified ways civil and environmental engineers could assist in building resilience into CRR programs based on the researchers own knowledge as a master’s level student in the field.
RQ3 used the same described in section 3.1.1. The topics covered in the survey to address Task 3a and 3b were 1) operational changes made by the CRR program in response to the COVID-19 pandemic, 2) future operational changes planned for the CRR program as a result of the COVID-19 pandemic, 3) the respondents’ assessment of the resilience of their operation amid the COVID-19 pandemic, and 4) the respondents’ assessment of the resilience of their operation going forward in the short term. A key subset of the questions asked to address these topics included, “If your program has made any operational changes to respond to COVID-19 to date, please describe,” “If your program is planning on making any future operational changes based on your experience with COVID-19 to date, please describe,” “How effectively do you think your coral reef restoration program was able to adjust to the disruption caused by COVID-19?”, and “When the disruptions caused by the COVID-19 pandemic are over, how well do you think your program will be performing compared to the same time of year before the pandemic began?”

3.2 Country COVID-19 Timeline

A timeline of COVID-19 in the country/region of each CRR program was constructed to help the author consider the context of the COVID-19 pandemic at each site. The factors considered in this timeline were 1) date COVID-19 entered the country, 2) date of first COVID-19 related death, 3) total number of confirmed cases by survey start date, and 4) total number of COVID-19 related deaths by survey start date. These data were compared to the total population of each country/region. Data for these questions were compiled from the John Hopkins GitHub by Mr. John Hunte. The COVID-19 data was collected for this study on September 4th, 2020, and consequently the data is only reported up to that date; surveys were distributed and completed between September 3rd and 14th, 2020.
3.3 Data Analysis

The results of the survey were analyzed using accepted qualitative data analysis methods through hand coding, using standard qualitative thematic coding methods, and the use of Excel software to visually represent the data (Russell, 2006). The multiple-choice answers were graphed to determine the incidence rate. The open-answer questions were read and coded using word and theme counts to identify frequently occurring themes in reference to the research questions of this study. Where appropriate, these frequently occurring themes were also used to generate graphs and figures to better display the data. The patterns and themes of disruption discovered during this analysis were then organized into a visual map to address Task 3c and 3d. The visual map included planned and enacted adaptions to these disruptions reported by the respondents. Possible engineering interactions were identified by the author based on the respondents’ answers. These analyses were performed following the methods of an exploratory study using rapid ethnographic small sample size methods appropriate for the time frame and focus stakeholder group of the study (Nabong, 2020; Taplin et al., 2002).

3.4 Ethics

The methods that include human subjects research were conducted according to the USF Institutional Review Board approved study (IRB STUDY001053). The study’s approval letter is provided in Appendix A. This study was supported by the United States Department of Education Graduate Assistance in Areas of National Need (GAANN) program and the larger National Science Foundation Research Traineeship “Systems Training for Research on Geography-based Coasts” (also known as STRONG Coasts) from the University of South Florida.
Participants were briefed on the purpose of the study and informed consent was received before participants took the survey. Participants were also informed that participation was voluntary. Each participant’s privacy and confidentiality were respected in this study. Real names were omitted from this study.
Chapter 4: Results and Discussion

The goal of this research was to understand how the global disruption of humans caused by the COVID-19 pandemic has impacted Tropical West Atlantic coral reef restoration programs and the reefs they serve, and to identify strategies to build resilience to global disruptions into these programs and other coral reef restoration programs. This chapter presents the results of the previously stated research questions and subsequent tasks and discusses these findings considering the overall research goal.

Eleven respondents participated in this study, with minimum and maximum times of completion of between 9 minutes, 13 seconds and 72 minutes, 40 seconds, respectively. The countries/regions represented by the respondents were the Bahamas (1), Barbados (1), Belize (1), Colombia(1), Dominican Republic (1), Jamaica (2), Saint Lucia (1), Florida and Puerto Rico (1) and the US Virgin Islands (2). Despite their varying locations of operations, all but one respondent agreed the COVID-19 pandemic had begun to impact the community served by their CRR program by mid-March or early April. One respondent answered that impacts were felt “a couple of months after the closure of tourism.”

The programs represented by the 11 respondents, while all CRR programs in the TWA, differ from each other in size, nursery and outplant methodology, and funding scheme, among other factors. Some are registered as NGOs, such as Fragments of Hope Ltd in Belize, and some are run as businesses, such as the CRR consultation program of Seascape Caribbean in Jamaica. Many are led by North American based marine scientists who settle in the Caribbean, but some are managed by local marine scientists, such as Oracabessa Fish Sanctuary in Jamaica. Some are
run and funded by hotels that start foundations, like the Punta Cana resorts in the Dominican Republic, while others are funded by larger NGOs and some are run by universities, such as the University of the Virgin Islands. While the exact number of registered coral restoration organizations or companies was not compiled for this study, those interviewed represent one of the major restoration entities in each country, and in some cases, the only one or one of two.

Every CRR site also exists within a different context. This context is influenced by the country/region in which they work, the political processes of that country/region, the population, socioeconomic status, and culture of their country and surrounding communities, the amount of tourism to their location, and the level of degradation to their focus reef(s), among other things. These variations in context and program scheme means each of the programs represented by the respondents will have experienced the impact of COVID-19 differently, facing disruptions, challenges, and changes not necessarily experienced by other TWA CRR sites. It is the goal of this section to aggregate these unique experiences to identify underlying trends. This will hopefully lead to the discovery of common disruptions and the identification of the root causes behind them, illuminating effective strategies for CRR practitioners and engineers to increase the resilience of CRR programs to future widespread disruptions.

The sample size of 11 was appropriate for this study as an exploratory rapid ethnographic assessment of specific stakeholder group within a limited time frame (Nabong, 2020; Taplin et al., 2002). While future studies could benefit from larger sample sizes, the sample achieved for this study was sufficient to address the proposed research question. This is especially true when considering the respondents represent 10 different countries and therefore the impact of COVID-19 on CRR programs in 10 different socio-cultural, socio-political, and socio-ecological
contexts. Any trends discovered between these respondents’ experiences likely represent trends that would hold true among larger sample sizes.

4.1 Research Question 1: The Impact of COVID-19 on Tropical West Atlantic Coral Reef Restoration Programs

Research Question 1 sought to investigate how the COVID-19 pandemic had impacted and was impacting CRR programs in the TWA. Task 1a sought to answer the “what”, identifying the specific ways in which TWA CRR programs were affected. Task 1b sought to answer the “why”, identifying the common causes of these impacts.

4.1.1 Task 1a: What CRR Activities were/are Impacted?

In the survey presented to them, TWA CRR practitioners (n=11) selected from a provided list of common coral gardening CRR activities which, if any, of the activities were/had been disrupted at their program. The respondents were not given a definition of “disrupted”, nor were they asked to share their own. As such, there is likely variance in what qualified as “disrupted” from respondent to respondent. Their responses, converted into percentages, are displayed in Figure 12.

The activities most commonly indicated to have been disrupted by the COVID-19 pandemic were data collection, data analysis, and outplant reef monitoring, which were each selected by 10 of the 11 respondents (91%). Outplanting (73%), donor fragment collection (73%), nursery site monitoring (64%), nursery site maintenance (64%), and outplant reef maintenance (55%), were also disrupted at over half the sites, suggesting that every step of the CRR process was disrupted during the COVID-19 pandemic. Planned expansion of CRR programs, represented by outplanting site development (36%), nursery site development (36%), new outplanting site identification (27%), and new nursery site identification (18%), were also
disrupted, though with less frequency than the more regular reef restoration activities listed above.

Several sites indicated disruptions to the human-engagement components of their reef restoration program, with seven (64%) respondents indicating disruption to educational outreach and four (36%) indicating disruption to community engagement work. Access to and maintenance of the equipment used in CRR were also impacted at some sites, with four respondents indicating disruption to purchasing gear/equipment (36%) and one respondent indicating disruption to boat/gear maintenance (9%).

To further analyze the common coral gardening CRR activities disrupted by the COVID-19 pandemic, the 17 proposed activities were sorted into 10 categories representative of stages in the CRR process and categories of peripheral activities (Table 2). These stages of coral gardening were informed by the Reef Resilience Network (2018) guide to coral gardening and included nursery site creation, coral fragment collection, nursery upkeep, outplant site creation,
outplanting, and outplant site upkeep. The categories of common peripheral activities were established as equipment, analysis, and outreach. Responses of other were categorized as other.

Table 2: Percentage of respondents experiencing disruption to common coral reef restoration activities, both as individual activities and by category

<table>
<thead>
<tr>
<th>Common coral reef restoration activities within category</th>
<th>% activities disrupted by reef restoration program</th>
<th>Categories of common coral reef restoration activities</th>
<th>Average % activities disrupted within category</th>
</tr>
</thead>
<tbody>
<tr>
<td>new nursery site identification</td>
<td>18%</td>
<td>Nursery site creation</td>
<td>27%</td>
</tr>
<tr>
<td>nursery site development</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>collecting donor fragments</td>
<td>73%</td>
<td>Coral fragment collection</td>
<td>73%</td>
</tr>
<tr>
<td>nursery monitoring</td>
<td>64%</td>
<td>Nursery upkeep</td>
<td>64%</td>
</tr>
<tr>
<td>nursery maintenance</td>
<td>64%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>new outplanting site identification</td>
<td>27%</td>
<td>Outplant site creation</td>
<td>32%</td>
</tr>
<tr>
<td>outplanting site development</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>outplanting</td>
<td>73%</td>
<td>Outplanting</td>
<td>73%</td>
</tr>
<tr>
<td>outplant reef monitoring</td>
<td>91%</td>
<td>Outplant site upkeep</td>
<td>73%</td>
</tr>
<tr>
<td>outplant reef maintenance</td>
<td>55%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>boat/gear maintenance</td>
<td>9%</td>
<td>Equipment</td>
<td>23%</td>
</tr>
<tr>
<td>purchasing gear/equipment</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>data collection</td>
<td>91%</td>
<td>Analysis</td>
<td>91%</td>
</tr>
<tr>
<td>data analysis</td>
<td>91%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>educational outreach</td>
<td>64%</td>
<td>Outreach</td>
<td>50.0%</td>
</tr>
<tr>
<td>community engagement</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>18%</td>
<td>Other</td>
<td>18%</td>
</tr>
</tbody>
</table>
While these stages do follow a somewhat linear progression, following the order listed, it is important to note that in many coral gardening CRR programs, several of these stages will occur simultaneously, especially after the initial nursery and outplant sites are established and the CRR programs seek to expand by identifying and developing new sites.

When displayed by average disruption rate within each category (Figure 13: Average percentage of respondents experiencing disruption to CRR activities within given category), the category that had the highest average indication of disruption were analysis (91%). The categories representing day-to-day coral gardening work, as opposed to the creation of new sites, also showed high average disruption rates with coral fragment collection, outplanting, and outplant site upkeep all having an average disruption rate of 73%, and nursery upkeep with a rate of 64%. Outreach activities were also significantly disrupted, with an average disruption rate of 50%.

Nursery site creation and outplant site creation had relatively low average disruption rates, 27% and 32% respectively. While these data would seem to indicate that the COVID-19 pandemic did not largely impact CRR programs’ ability to create new nursery outplanting sites, this is possible because respondents were asked to only report disruption to planned activities. As the creation of new sites is a relatively infrequent CRR activity, many of the surveyed programs may not have had program expansion activities planned for the season affected by COVID-19 and therefore not reported these activities as disrupted. Equipment related activities and other activities were also not commonly disrupted, with averages of 23% and 18% respectively.

When interpreting these data, it is important to note that CRR programs often perform certain tasks seasonally, e.g. they would not outplant right before hurricane season, since the new outplants might not have enough time to attach properly before the first storm. Furthermore,
different CRR programs follow different schedules on when to implement each stage of the coral gardening process. Consequently, it cannot be assumed all the coral gardening CRR programs surveyed had the same activities planned when the COVID-19 pandemic began. Therefore, it is unlikely that all 11 respondents had all 17 activities planned for the season impacted by the COVID-19 pandemic.

![Figure 13: Average percentage of respondents experiencing disruption to CRR activities within given category](image)

While the data displayed in Figures 12 and 13 can help discover what activities were most disrupted among TWA CRR programs during the COVID-19 pandemic in general, it should be understood that it cannot be know from this data if a disruption rate below 100% for a certain activity is because some of the programs did not experience disruption to this activity, or simply because some of the respondents did not have this activity planned. It also means that if the COVID-19 pandemic had begun during a different season the results found in this survey might have differed.
Of the 17 activities (including other) presented, the median amount of activities indicated by a single respondent as disrupted was 9, with a maximum amount indicated of 15 and a minimum amount indicated of 1, where the respondent selected only other. As shown in Figure 14, 50% of the respondents reported between 8 and 11 of the proposed activities were/are disrupted at their program due to COVID-19. Every CRR activity presented in the survey was identified as being disrupted by at least one CRR program, indicating the COVID-19 pandemic disrupted every major coral reef restoration activity, albeit different activities and to differing degrees at each site.

Two respondents indicated “other” disruptions than the options presented and elaborated in the text-entry box on those other disruptions. One respondent indicated a disruption in boat travel ability due to government-imposed travel restrictions. This phenomenon will be discussed in the next section. The other respondent indicated a disruption to the hiring of new staff, especially from abroad. Hiring holds and decreased staffing ability were also reported by other respondents, and will be discussed in the next section.

Figure 14: Box and whisker plot of distribution of number of activities reported disrupted at each program out of a maximum of 17 activities. n=11.
4.1.2 Task 1b: Why These CRR Activities were/are Impacted

The survey of TWA CRR practitioners asked several questions to explore the ways in which the COVID-19 pandemic directly or indirectly led to the disruption of CRR activities discussed in section 4.1.1. These causes were presented in categories including Basic Needs, Government Protocols, Money, Health, Family and Community, and Tourism. The percentages of respondents indicating a specific cause of disruption are presented in Figure 15.

Figure 15: Percentage of respondents (n=11) experiencing each specific cause of disruption to the planned activities of their coral reef restoration program

The two most reported causes of disruption were both directly related to COVID-19, with 9 respondents reporting government mandated stay-in-place orders (82%) and 8 reporting fear of
personally contracting COVID-19 (73%). Disruption driven by lack of tourism was also highly cited, especially considering that an error in the survey only allowed for respondents to choose one disruption within the tourism category. Six respondents (55%) indicated lack of tourist volunteers and two respondents (18%) indicated lack of tourist fees as disruptions, meaning eight respondents overall (73%) reported disruption directly caused by lack of tourism.

Fear of passing COVID-19 to a family member or friend was also commonly cited, indicated by 5 respondents (45%), though only 2 respondents cited family obligations caused by COVID-19 (18%) and no respondents indicated that things were disrupted by themselves becoming sick with COVID-19.

![Estimated COVID-19 Cases at Respondent Sites](image)

**Figure 16:** Number of cases of COVID-19 in the communities served by each coral reef restoration program as estimated by respondents n=11 (estimates have not been verified)

Respondents were asked to indicate whether COVID-19 had entered the community their CRR program serves and, if so, how many people in the community had contracted the disease, as displayed in Figure 16. It is interesting that while 8 respondents reported fear of personally contracting COVID-19 as a disruption to their CRR work, only six respondents (55%) reported their community having had any COVID-19 cases. The global COVID-19 pandemic has impacted areas without cases of the disease, as illustrated by the fact that only 6 -7 of the 11
CRR programs surveyed reported having COVID-19 cases in their community, but all 11 report having had their CRR activities disrupted by the COVID-19 pandemic (Figure 12).

To address Task 1c, data of COVID-19 confirmed cases and deaths were collected. These data are displayed alongside country population and the date the first COVID-19 case was confirmed in each country in Table 2: COVID-19 Data by Country as of Sept. 4th, 2020.

Table 3: COVID-19 Data by Country as of Sept. 4th, 2020. Source: John Hopkins GitHub, summarized by Mr. John Hunte

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Total Population</th>
<th>Total Confirmed Cases</th>
<th>% population</th>
<th>First Case</th>
<th>First Death</th>
<th>Total deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahamas</td>
<td>393,244</td>
<td>2386</td>
<td>0.61%</td>
<td>16-Mar</td>
<td>31-Mar</td>
<td>50</td>
</tr>
<tr>
<td>Barbados</td>
<td>286,641</td>
<td>178</td>
<td>0.06%</td>
<td>17-Mar</td>
<td>4-Apr</td>
<td>7</td>
</tr>
<tr>
<td>Belize</td>
<td>383,071</td>
<td>1152</td>
<td>0.30%</td>
<td>23-Mar</td>
<td>5-Apr</td>
<td>15</td>
</tr>
<tr>
<td>Colombia</td>
<td>49,650,000</td>
<td>641574</td>
<td>1.29%</td>
<td>6-Mar</td>
<td>21-Mar</td>
<td>20618</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>10,630,000</td>
<td>96629</td>
<td>0.91%</td>
<td>1-Mar</td>
<td>16-Mar</td>
<td>1801</td>
</tr>
<tr>
<td>Jamaica</td>
<td>2,935,000</td>
<td>2964</td>
<td>0.10%</td>
<td>11-Mar</td>
<td>18-Mar</td>
<td>30</td>
</tr>
<tr>
<td>Saint Lucia</td>
<td>181,889</td>
<td>26</td>
<td>0.01%</td>
<td>14-Mar</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>Florida</td>
<td>21,480,000</td>
<td>640211</td>
<td>2.98%</td>
<td>2-Mar</td>
<td>7-Mar</td>
<td>11750</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>3,190,000</td>
<td>34241</td>
<td>1.07%</td>
<td>16-Mar</td>
<td>20-Mar</td>
<td>455</td>
</tr>
<tr>
<td>US Virgin Islands</td>
<td>106,977</td>
<td>1150</td>
<td>1.07%</td>
<td>16-Mar</td>
<td>4-Apr</td>
<td>16</td>
</tr>
</tbody>
</table>
One way respondents indicated that COVID-19 indirectly disrupted their operations was through government protocols put in place to address COVID-19. While only one respondent cites experiencing a government mandated shutdown of restoration operations (9%), five indicate a government mandated curfew as a source of disruption (45%). Stay-in-place orders were the most cited source of disruption, indicated by 9 of 11 (82%) respondents as impacting their program’s ability to perform planned activities. One respondent explained how these government protocols disrupted their CRR operations by reporting, “the (Government) severely restricted people’s ability to boat for months during the pandemic, including us despite getting an exemption from the Government to keep operating our farm.” This suggests that while COVID-19 did not directly infect any of the surveyed CRR practitioners and was only present in 55%-64% of the CRR programs’ communities, broad sweeping government policies meant to manage the spread of the virus directly impacted these CRR operations. This is not an argument that such government policies are misguided; it simply shows that global disruptions like the COVID-19 pandemic can have implications far beyond the actual event.

Financial matters were the next most frequently indicated category of causes of disruption. Seven respondents (64%) indicated uncertainty about future funding as a disruption to their planned operations, the third most of any option. Lack of operation funding was indicated by five respondents (45%) and lack of employee funding was indicated by four respondents (36%). No respondents indicated an increase in cost of maintaining operations, therefore the lack of funding was most likely due to decreased available funds from traditional sources.

When surveyed on their traditional forms of funding, 10 respondents (91%) indicated receiving funding through competitive grants, eight (73%) indicated donation, six (55%) indicated private partnership, three (27%) indicated national government loans/funds and
tourism fees/other fees, and two (18%) reported receiving funding from foreign government loans/funds (Figure 17). When reporting whether these forms of funding had been impacted due to COVID-19, seven respondents (64%) indicated that some or all their funding sources had been impacted. The respondents were also given the option to indicate that funding had increased within any category, but none reported that this had happened.

Respondents were then asked to explain how their funding had been decreased, and their responses were coded to extrapolate which funding categories had decreased due to COVID-19. Any explicit mentioning of a source of funding changing was quantified as one respondent experiencing a decrease in that area of funding, and the totals of this quantification are displayed in Figure 17. It is possible that some respondents experienced a decrease in funding in more categories than they explicitly mentioned. At least one respondent experienced decreases in funding from each of the categories of funding except national government loans/funds. 25% of respondents’ donation funds decreased, 40% of competitive grant funds decreased, 50% of
private partnership and foreign government loans/funds decreased, and 100% of tourism fees/other fees funding decreased. Respondents indicated the main drivers behind these funding decreases to be 1) lack of international travel 2) diminished budgets of corporate clients/partners/donors for the new fiscal year (June 2020 -June 2021) 3) lack of tourist and 4) general inability to perform restoration work.

The lack of tourism was an important theme within the respondents’ reasons for COVID-19-caused disruptions. Financially, tourism-based funding decreased universally during COVID-19, as can be seen in Figure 17. This decrease in tourism is largely due to closed boarders and travel bans enforced during the COVID-19 pandemic. One of the respondents explained this financial situation in their survey, reporting, “No eco-tourism has taken place since March 2020. We charge entrance fees to our coral farm - which serves as a tourism attraction and community education center while we grow corals for restoration – as a way to fund our projects.” The COVID-19 pandemic’s elimination of tourism removed this source of funding from this program, and simultaneously disrupted the program’s educational outreach and community engagement. This funding reduction scenario was also expressed by two other respondents.

The lack of tourism impacted CRR in the TWA beyond funding; 55% of respondents indicated the lack of tourist volunteers as a cause of disruption to their operations (Figure 15). This indicates that volunteer workers, often called eco-tourists or voluntourists, served as a significant portion of the workforce for many of the surveyed CRR programs. One respondent explained this relationship in their survey, stating, “We typically have an operational (volunteer) citizen science program through local dive shops. The citizen scientists help us to maintain the nurseries through cleaning and data collection.” The respondent goes on to explain, “we have not been able to have one of these dives since the local dive shops have not been operational due to
Another respondent explained how the pandemic has upset this tourist-volunteer-as-workforce relationship in stating, “[It is] difficult to get dive shops involved with coral nursery maintenance since they do not have as many tourists.”

To further explore how workforce availability was altered by the COVID-19 pandemic, respondents were asked to report any changes in their program’s workforce due to COVID-19. Figure 18 shows that within the respondents’ programs, full-time workers were the least affected by COVID-19, with 55% of the respondents reporting an increase or no-change in full-time workers and only 27% reporting a decrease. Part-time workers and trainees both fared worse than full-time workers with 27% of respondents reporting an increase or no-change and 55% reporting a decrease in both categories. The volunteer workforce of TWA CRR programs was heavily affected, with only one respondent (9%) reporting no-change and eight respondents (73%) reporting a decrease in volunteers.

Figure 18: Workforce Change of CRR Programs amid COVID-19
It is important to note that this decrease in volunteers did not automatically cause
disruption to a CRR program’s planned activities; while eight respondents indicated an increase
in volunteers, only six reported *lack of tourist volunteers* as a disrupting factor. Yet, at least four
respondents mentioned “staffing”, “lack of healthy volunteers”, or “vaccinated individuals” as
something needed to enable work, indicating lack of a reliable workforce as a common issue in
CRR amid COVID-19.

4.2 Results for RQ2: Impact of COVID-19 on Reef Health

Research Question 2 sought to explore how the COVID-19 human pandemic was/is
indirectly impacting the vitality of the coral reef ecosystems monitored/restored by TWA coral
reef restoration programs. Task 2a was to survey TWA CRR practitioners to identify changes in
reef health during COVID-19 pandemic. Task 2b was likewise to identify likely causes of
changes in the reef ecosystem health through assessing observations and opinions of TWA CRR
practitioners given in the survey.

Surveyed CRR practitioners noted different impacts to reef health due to the COVID-19
pandemic (Figure 20). These perceptions of reef health change are based on eye-witness
accounts of the respondents, or from conversation between survey respondents and other reef
users. These claims have not been verified, but they are still beneficial in identifying themes in
reef health change during COVID-19.

Two respondents (18%) noted no noticeable changes in their reef sites. Two (18%) noted
that their coral fragments and outplants had survived and grown well and coral health was
overall good, despite the lack of monitoring. Four respondents (36%) noticed the presence of
stony coral tissue loss disease (SCTLD) negatively impacting overall coral health, although one
of these four made clear that the disease was not impacting their specific outplants. Finally, four respondents reported less and/or smaller reef fish in their reef restoration sites.

The causes of these changes in reef health can be broken down into two categories: non-human and human. The most significant non-human impact to reef health during COVID-19 is SCTLD (Figure 19), aptly referred to as the “coral pandemic”. First reported in Florida in 2014, SCTLD has spread to much of the TWA, including Jamaica, the United States Virgin Islands, Belize, the Dominican Republic, Grand Bahama and Puerto Rico. The cause of the disease is yet unknown, yet it can infect over 20 different species of coral. The disease spreads quickly and has high mortality, especially on already stressed reefs (AGRRA, 2020). While SCTLD is not caused by COVID-19, the disruption to human society and CRR activities caused by the COVID-19 pandemic may have had indirect impacts on the spread of this coral pandemic. See Discussion for more on this.

Figure 19: Stoney Coral Tissue Loss Disease on Great Star Coral (Montastrea cavernosa) in the Florida Keys. Photo taken in September 2018. Copyright FWC Fish and Wildlife Research Institute and used under Creative Commons license Attribution-NonCommercial-NoDerivs 2.0.
The second category of cause of change, human impact, is driven by changes in human use of the coral reef ecosystems during COVID-19. These human use changes have had both positive and negative - and often nuanced – impacts on reef health. The first major reef-use change driven by the COVID-19 pandemic was in the swift and nearly complete removal of tourists and recreational users of the reefs and reef-adjacent areas. This was noted by some respondents to have had some positive impact on reef ecosystem health, eliminating swimmer, snorkeler and other human-use damage to reefs. This view was echoed by community members from one of the respondent’s site. The CRR practitioner reported that, “a few people have mentioned [to us] that the sites look better and they attribute this improvement to the lack of people in the sea and on the beaches during lock down.” However, this lack of tourists/recreational users has also had negative impacts on the CRR programs themselves, as noted in section 4.1.2.

Figure 20: Change in coral reef ecosystem health in the Tropical West Atlantic during COVID-19 pandemic as reported by surveyed reef restoration practitioners. Note: one respondent indicated both "coral growth" and "SCTLD" resulting in a n=12
The second major change in human use of reefs noted by respondents was fishing behaviors. Three of the four respondents that reported less and smaller reef fish explicitly linked this change to an increase of fishing in their comments. Likewise, three respondents (27%) indicated *improper community use of reefs* as disrupting their CRR activities (Figure 15). A definition of “improper use” was not given to respondents, nor were they asked to report a definition of “improper use”. As such, what constituted “improper use” was based entirely on the perception of the respondent. Additionally, as mentioned above, these perceptions of reef health change, including fish population change, are based on eye-witness accounts and not on scientifically collected data.

A decrease in size and numbers of reef fish can have major negative impacts on reef ecosystem health. As discussed in section 2.5.1.3 Overfishing, herbivorous reef fish are necessary for reef health as they control macro-algal takeovers. Large, mature herbivorous fish are likewise important in that the largest female fish produce exponentially more eggs than their smaller counterparts, helping to replace the fish that are hunted by humans and keep human fishing practices sustainable. The respondents’ observations of less and smaller reef fish suggest unsustainable fishing practices which can lead to an overall decrease of reef health. Additionally, one respondent reported damage to the reef itself due to an increase in fishing, including breakage of the corals from nets and spear-guns.

Overall, the impact of COVID-19 on the health of the coral reefs served by the survey respondents seems to be site specific. If the site has/is experiencing increased fishing pressures, the health of the reef ecosystem has likely worsened. If the site has been exposed to SCTLD, the coral health may have decreased or remained similar to pre-COVID-19 conditions. If the reef is experiencing neither of these pressures, it is likely that the decrease in human recreational
activity has improved reef health. Again, it is important to note these conclusions are based on respondent observation and not quantitative data, so they should be treated as hypotheses, not facts.

4.3 Research Question 3: Resilience of CRR Programs and the Reefs They Serve

4.3.1 Current and Planned Adaptations to COVID-19 by CRR Programs

RQ3 sought to answer how CRR programs could be more resilient to future global-scale disruptions. Task 3a was to identify methods used by CRR programs to respond to the COVID-19 disruption through survey of TWA CRR practitioners survey. Task 3b was to identify future methods planned by CRR programs to respond to COVID-19 disruption through survey of TWA CRR practitioners and Task 3c was compare these responses to current program resilience as assessed by respondents and major disrupting influences identified in Task 1b and 2b to identify likely leverage points in building increased resilience into CRR programs. Task 3d was to identify areas where civil and environmental engineers can assist in building resilience into CRR programs.

When asked to report any changes their CRR program had made to date in response to the COVID-19 pandemic, two respondents (18%) reported only decreases in productivity due to inability to travel, reduced workforce, reduced workdays, and inability to plan. All other respondents reported at least some adaptation to the COVID-19 pandemic and the disruptions it caused. Three respondents (27%) described adapting to new governmental protocols by seeking special permissions to continue operations, arguing that their work was “time sensitive” which allowed them to procure exceptions to travel restrictions and stay-in-place orders. Two respondents (18%) reported employing COVID-19 prevention tactics within their programs.
including social distancing, wearing masks, and, in one case, “establish[ing] dive teams to keep interactions low [with] mandated mask use and decontamination protocols for dive gear.”

The other four respondents (36%) indicated significant changes to their program operations in response to COVID-19. One respondent reported their restoration team had, “decided to go on less diving trips and more snorkeling trips to monitor and maintain our fragments”. Another respondent has switched focus to employing locals, securing an emergency grant to fund a local team at one location, and making new hires of diving instructors at another to maintain the coral restoration programs after the “closure of the resort and impossibility of flying” crippled their previous workforce. A third respondent described switching focus to data analysis and grant writing during the pandemic. A final respondent reported an unexpected positive outcome adapting to reduced staff during the pandemic. They explained, “Reduced staff [led to] me having to do all [the CRR fieldwork] myself and [this] has improved outplant survivorship and allowed me to get first-hand feedback as to programmatic issues to make the next project(s) more fruitful.”

When asked if their program was planning on making any additional operational changes based on their experience with COVID-19 (Figure 21), five respondents (45%) reported no changes planned. Of the six respondents who reported plans for future changes, two respondents (18%) described changes to be enacted/maintained throughout the COVID-19 pandemic only, while the remaining four (36%) described operational changes that would continue in the long term.
The two COVID-19 specific planned adaptations reported were working within government regulations by seeking permission for fieldwork on a dive-by-dive basis and the continuation of one respondent’s program-wide switch from diving trips to snorkeling trips to monitor and maintain fragments. The long-term planned operational adaptations included developing virtual “distance-learning” coral workshops to overcome travel bans, implementing the programmatic methodological improvements discovered during the pandemic, developing a large team of paid local workers to maintain nurseries and perform outplantings, and restructuring the CRR program as a governmental program to secure annual funding. The respondents were asked to rate effectiveness of their program in adapting to COVID-19 on a scale of 0 to 5. The maximum rating was 4 compared to a minimum rating of 1. The average rating for program adaptation effectiveness was 3.05, the median rating was 3, and the mode rating was a tie between 3 and 4.

Of the eleven respondents, only one (9%) reported that their CRR program was currently unable to perform some or all of their planned work; the other 10 (91%) reported they were able to perform some, but not all of their planned work. When asked how they thought their CRR program would be performing after the end of the COVID-19 pandemic versus the same season
as the year before the COVID-19 pandemic began, two (18%) responded *much better*, one (9%) responded *somewhat better*, four (36%) responded *about the same*, three (27%) responded *somewhat worse*, and one (9%) responded *much worse*. These responses of each respondent, along with their reported operation changes, are displayed together in Table 2.

Respondents were also asked to rate the effectiveness of the community(ies) served by their program in adapting to COVID-19 on a scale of 0 to 5. The maximum rating was 4 compared to a minimum rating of 2. The average rating for community adaptation effectiveness was 2.95, the median was 3, and the mode was 3. Six respondents (55%) rated their CRR program as having more effectively adapted to COVID-19 than the community they served, with an average difference of 0.83. Two respondents (18%) rated their program and the community they serve as equally effective in adapting to COVID-19. The remaining three respondents (27%) rated the community they serve as more effective in adapting to COVID-19 than their CRR program, with an average difference of 1.3. A graph of these responses can be seen in Figure 22.

![Figure 22: Effectiveness in Adaptation to COVID-19 of CRR programs and the communities they serve as reported by respondents (n=11)](image-url)
Table 4: CRR Program Changes Implemented and Planned in Response to COVID-19 alongside adaptation rating and post-COVID-19 performance prediction

<table>
<thead>
<tr>
<th>#R</th>
<th>Operational Changes To-Date</th>
<th>Planned COVID-19 Specific Changes</th>
<th>Planned Long-Term Changes</th>
<th>Program Adaptation Rating</th>
<th>Performance after COVID-19 vs Year Before</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No travel, volunteers, or training workshops</td>
<td>Develop distance learning coral workshops/trainings</td>
<td>Develop distance learning coral workshops/trainings</td>
<td>3</td>
<td>Somewhat worse</td>
</tr>
<tr>
<td>2</td>
<td>Reduced activity; less workdays</td>
<td>None</td>
<td>None</td>
<td>2.5</td>
<td>Much worse</td>
</tr>
<tr>
<td>3</td>
<td>Non-rotating dive teams, mandated masks and decontamination</td>
<td>None</td>
<td>None</td>
<td>4</td>
<td>About the same</td>
</tr>
<tr>
<td>4</td>
<td>Reduced staff, reduced productivity – but improved methodology</td>
<td>None</td>
<td>Implement methodology improvements, both short-term / long-term</td>
<td>3</td>
<td>Much better</td>
</tr>
<tr>
<td>5</td>
<td>Boating limited, proper government exemptions obtained</td>
<td>None</td>
<td>None</td>
<td>3</td>
<td>About the same</td>
</tr>
<tr>
<td>6</td>
<td>Obtained permission for field work on dive-by-dive basis</td>
<td>Obtain permission for field work on dive-by-dive basis</td>
<td>None</td>
<td>4</td>
<td>Somewhat better</td>
</tr>
<tr>
<td>7</td>
<td>Social distancing, masks</td>
<td>None</td>
<td>None</td>
<td>1</td>
<td>Somewhat worse</td>
</tr>
<tr>
<td>8</td>
<td>Focus on data analysis and grant writing</td>
<td>None</td>
<td>Restructure program as government project with annual funding</td>
<td>2</td>
<td>Much better</td>
</tr>
<tr>
<td>9</td>
<td>Secured emergency grant for local team, hired local dive instructors for nursery work</td>
<td>None</td>
<td>Develop larger team of paid local workers to perform CCR work</td>
<td>4</td>
<td>About the same</td>
</tr>
<tr>
<td>10</td>
<td>Obtained government permission to operate throughout shutdown</td>
<td>None</td>
<td>None</td>
<td>4</td>
<td>Somewhat worse</td>
</tr>
<tr>
<td>11</td>
<td>Less diving and more snorkeling for monitoring/maintenance</td>
<td>Less diving and more snorkeling for monitoring/maintenance</td>
<td>Less diving and more snorkeling for monitoring/maintenance</td>
<td>3</td>
<td>About the same</td>
</tr>
</tbody>
</table>

When asked to describe any changes to the surrounding community’s opinion of their program reef restoration site(s), most respondents (64%) did not indicate that they had noticed any changes. One of the remaining four respondents reported that a CRR project in one community had been put on hold. The other three respondents reported positive change. One
respondent remarked that community members were reporting the health of the restoration site looked like it was improving during the pandemic. Another respondent wrote of their program’s increased social media presence during the pandemic, stating they, “have had positive impressions from the community through this outreach.” A third respondent wrote positively on the impact of COVID-19 pandemic on the surrounding communities’ opinion of their CRR program stating, “If anything, community opinion has gotten more favorable. There already was a positive reaction generally to our work, but healthy reefs providing food security and economic benefits, recreational activities, and coastal protection from recent hurricanes highlighted their value to many people.”

When asked what, if anything, their program needed to continue their restoration work throughout the duration of the pandemic, seven (64%) of the respondents mentioned funding and four (36%) mentioned a reliable, healthy workforce. Other themes within these responses were ability to plan, transportation (of humans and coral samples), and equipment.

4.3.2 Comparing Adaption Strategies to Major Disruption Causes

The main obstacles to continuing CRR work, as identified in Task 1b, were the lack of financial uncertainty, lack of reliable workforce, and inability to access field sites. Based on the responses, these obstacles were mainly driven by decreased numbers of, or elimination of tourists due to closed borders and fear of contracting COVID-19. General interruptions of human systems impacting CRR programs were others’ ability to plan, and government protocols (specifically stay-at-home orders and boating restrictions). The CRR programs surveyed responses to these challenges included securing permission to operate on-site, implementing on-site protections against the spread of COVID-19 such as mask wearing, personally fulfilling roles left vacant by decreased workforce, switching focus from field work to data analysis,
fundraising, and social media outreach. To improve operational resilience to future disruption events, CRR plans included securing an annual budget by transitioning to a governmental program, diversifying funding, and developing a local workforce.

The main drivers of impact to reef health amid the COVID-19 pandemic, as identified in Task 2b, were SCTLD and reef fishing. SCTLD is not directly related to COVID-19, and no respondent indicated that the effects of the disease were worsened or lessened by the COVID-19 pandemic and its impacts on CRR restoration. It is possible that the COVID-19 human pandemic has indirectly impacted the effects of the SCTLD coral pandemic, but such information is outside the scope of this study. However, several respondents linked the COVID-19 pandemic to an increase in reef fishing and more damaging reef fishing. As this increase of damaging fishing was carried out by members of reef-adjacent communities and only after the onset of the COVID-19 pandemic, it is hypothesized to be linked to community loss of livelihood and increased food insecurity resulting from the dearth of tourism and disruption to human food systems. Four respondents mentioned the decline of fish populations and/or increase of damaging fishing practices, yet no respondent stated any planned or implemented action to address this phenomenon.

4.3.3 Intersections with Civil and Environmental Engineering

Based on the challenges experienced by CRR programs amid COVID-19 expressed in Section 4.3.2, the author has identified three key ways in which Civil and Environmental Engineers (CEEs) could assist in building resilience to future disruptions into TWA CRR programs. To address the key obstacles of reduced workforce and inability to access CRR sites, CEEs could work with CRR practitioners to develop long-distance monitoring systems for in-situ and ex-situ sites. For in-situ sites, this could be as simple as an aquatic drone with video camera
controlled from shore and sent to provide a visual check-up on the health and maintenance needs of a nursery or outplant site. For ex-situ sites, this could be developed as a simple visual monitoring system, or as a more complex systems capable of taking measurements and automatically controlling flows based on these measurements. Both monitoring systems would allow CRR practitioners to easily monitor their sites remotely, helping to alleviate the difficulties of lack of access to site and a diminished workforce. Depending on the goals of the CRR program, this remote monitoring could be designed for different technology and skill levels, opening the possibility of these systems being operated by local stakeholders within the reef adjacent communities.

To address the financial difficulties of TWA CRR programs, CEEs could help by partnering with CRR programs to develop well-funded NbS projects. CEEs and CRR practitioners could work together to develop restoration programs that take advantage of governmental and private-sector desire for coastal storm protection, erosion protection, and thriving tourism to exist simultaneously. CEEs and CRR practitioners could combine engineering knowledge and reef restoration knowledge to design structures that maximize coastal protection while simultaneously restoring reef areas and creating beautiful tourist destinations. Transitioning to CRR programs partnered with CEEs that brand themselves as ecological, economical (tourism), and infrastructural projects could help secure governmental and private partnerships funding that would allow CRR programs to operate confidently, even amid global disruptions. Additionally, securing government buy-in through this strategy could also make it easier for CRR programs to secure permission to operate in the event of another government mandated shutdown.
CEEs could also assist CRR programs in addressing the problem of increased reef fishing. As mentioned above, this increase in fishing during the COVID-19 pandemic is likely due to loss of livelihood and food insecurity within the reef-adjacent community(ies). Both issues could be at least partially alleviated by developing/improving local food infrastructure. CRR practitioners and reef-adjacent communities could work with CEEs to map the food-energy-water systems within their communities and discover opportunities where the local food systems could be strengthened. These opportunities might include the creation of gardens fertilized with urine diversion toilets, raising chickens on food scraps, or developing mariculture of seaweed (Estenia Ortiz Carabantes, 2020). Pursuing these opportunities would help create local food source alternatives to the reef fish. This would hopefully alleviate pressure from the reef, removing the incentives for damaging fishing practices.

The results of Tasks 1b, 2b & 3c are displayed visually in Figure 23. Figure 23 displays the connections between the COVID-19 pandemic, disruption to TWA CRR programs, and changes in coral reef health, as discovered through survey of 11 TWA CRR practitioners. The most impactful paths of disruption are marked with bold arrows. Adaptations by CRR programs and suggested synergies between CRR practitioners and CEEs are notated by dashed lines. Figure 23 shows 13 distinct adaptations of CRR programs to disruptions caused by the COVID-19 pandemic, indicating an average of greater than one adaptation per respondent. Figure 23 also displays that CRR programs had either implemented or planned operational changes to address every major disruption factor to their CRR program’s ability to operate. While no respondent indicated any planned operational change to address an increase in damaging fishing practices, the suggested CRR-CEEs synergy of mapping and improving the local food systems could address this underlying disruption to reef health.
Figure 23: Visual Map of the Impact of COVID-19 on TWA CRR Programs, reported adaptation strategies, and recommended CEE partnerships
4.4 Discussion

Several interesting trends were discovered through the course of this study. One was the somewhat intuitive reality that the impact of the COVID-19 pandemic extended far beyond human health, even impacting communities that did not experience a single case. While only six respondents reported that the community their CRR program serves in had at least one confirmed COVID-19 case up to the time of survey, all 11 reported their operations were disrupted by the COVID-19 pandemic. Based on the respondents’ responses, this universal disruption was most directly caused by government protocols blocking international travel and mandating stay-in-place orders. The lack of international travel disrupted tourism, a key component of funding and volunteer workers for many of the surveyed CRR programs. This lack of international travel also made it impossible for CRR programs to hire international workers, take on international contracts, or visit international partners, sites, or conferences. It also hindered internationally based CRR practitioners from returning to the site of their program. The mandatory stay-in-place orders and domestic travel bans enacted in some countries meant that some CRR practitioners could not return to work for extended periods of time, and that many CRR practitioners had to seek special permission from their governments to return to work. The disruption to data collection and analysis indicated by 91% of respondents is likely linked to the inability of CRR practitioners to visit their sites due to these travel restrictions and stay-at-home orders.

However, while every respondent reported their program as disrupted, their predictions of the overall impact of this disruption were varied. As mentioned in Section 4.3.1 Current and Planned Adaptations to COVID-19 by CRR Programs, when asked how they thought their CRR program would be performing after then end of the COVID-19 pandemic versus the same season
the year before the COVID-19 pandemic began, two (18%) responded much better, one (9%) responded somewhat better, four (36%) responded about the same, three (27%) responded somewhat worse, and one (9%) responded much worse. While this data trends slightly in the direction of “worse”, it is significant to note that three of the respondents predicted the improvement of their program operations after COVID-19. One respondent clearly clarified why, in explaining how the decrease in staff for their program led to them performing much of the field work they had long since delegated to others because of their need to perform administrative tasks. While this decrease in staff did decrease productivity, their involvement in field work allowed them to “get first-hand feedback”, leading to the discovery of “programmatic issues” that were driving down coral survivorship. Fixing these issues has led to “greatly improved… [coral] survivorship” in the short term and “larger programmatic actions to future works”. The other respondent predicting a much better post-COVID-19 program performance expressed that COVID-19 had all but halted their program in the short term, but that this allowed for time to focus on data analysis and planning. This shift resulted in a restructuring of the program as a government program, complete with both national and international funding. They are confident that once the program is able to start up again, their new direction, support, and funding will allow the CRR program to grow like never before. Of course, not every CRR program has similar optimism for the future. Four respondents expect their program to be performing somewhat worse to much worse than before the pandemic began. Most respondents reported largely trying their best to get by in the meantime, with little to no planned operational changes once the COVID-19 pandemic ends.

This variance in prediction of program performance post-COVID-19 pandemic is unsurprising given the unique context of each CRR program. As discussed at the beginning of
this chapter, the programs surveyed differed from each other not just in size, management style, and funding schemes, but also in political, cultural, and socioeconomic context. As such, it is likely each of the programs represented have experienced the impact of COVID-19 differently, facing disruptions and challenges not necessarily experienced by other TWA CRR sites. Considering this, the trends identified within the respondents’ answers indicate largely universal paths of disruptions for CRR programs during the COVID-19 pandemic, and perhaps other global disruptions.

It is interesting that while every CRR program was disrupted in their reef restoration activities, none reported any decrease to reef health directly related to this. The two respondents that mentioned any connection between the two noted that their outplants and nursery corals were growing well despite the lack of consistent monitoring. While this is certainly not enough data to draw any conclusions, it does seem to be positive for coral survivorship.

However, the COVID-19 pandemic to date has not been universally good for TWA coral reefs. As mentioned in Section 4.2 Results for RQ2: Impact of COVID-19 on Reef Health, four respondents reported declining fish populations, three of which directly linked this to an increase in reef fishing. It is hypothesized by the author that this increase in fishing pressures is largely driven by diminished livelihoods and food insecurity among the reef-adjacent communities. The COVID-19 pandemic and ensuing government protocols of stay-at-home orders, curfews, business closures, and travel restrictions have created breakdowns of food infrastructure in some regions, rendering entire communities food insecure. Additionally, COVID-19 and the ensuing shutdown eliminated many people’s employment/livelihood, also rendering them food insecure. These phenomena are documented by Daniel Velazques in his docuseries *Belize inna time of covid*. (Velazques, 2020) While there are many possible drivers of increased reef fishing during
the COVID-19 pandemic, it is possible food and livelihood insecurity driven by changes in government policies prompted individuals to increase their fishing pressure on the local reefs. This is evidenced by the fact that respondents reported this increased fishing started after the COVID-19 pandemic began and by one respondent’s report of the unusual “presence of fishermen from more distant communities”.

It is impossible to tell from the data collected if any of the respondents connected this increase in fishing to diminished livelihoods or food insecurity in the reef-adjacent communities, although none explicitly mentioned COVID-19 impacts on the community and only two respondents indicated lack of access to food as disrupting their CRR operations. Additionally, none of the respondents who reported declining fish populations proposed any methods for addressing community over-fishing. This may be because addressing overfishing is already part of the CRR program’s community outreach or that such outreach seemed outside of the scope of the questions asked in the survey. However, as discussed in Section 2.6.4, addressing socio-ecological aspects of restoration is exceptionally important to the success and resilience of CRR programs. As such, one recommended partnership between CRR practitioners and CEEs is improving food security in the reef-adjacent communities. A more immediate way that CRR programs could work to minimize the damages of reef fishing to the reef ecosystem health amid COVID-19 would be to run a social media campaign on sustainable fishing practices. One respondent reported increasing their social media presence during the COVID-19 pandemic being well received by their surrounding community. Other CRR programs could employ this tactic as a tool to combat damaging fishing practices. These campaigns could refrain from insisting that fishing stop, recognize that this fishing is coming out of a place of need, and instead co-create appropriate solutions with the local community on least damaging practices.
While this thesis is a case study of the COVID-19 pandemic, its findings have implications beyond this single event. Some of the disrupting factors of this COVID-19 case study – e.g. stay-at-home orders and social distancing - are specific to a pandemic event. However, many of the other disrupting factors - such as decreases in tourism, inability to access site(s), and financial uncertainty – are likely to occur in other major disruption events, such as economic crisis or natural disaster. As such, many of the stated adaptation strategies, both of the CRR practitioners and those recommended for partnership with CEEs, are important to the overall resilience of CRR programs in the face of any major disrupting event.

As displayed in Figure 23, every major disrupting factor to CRR activities was addressed by at least one planned/implemented operational adaptation. This is encouraging, since, as discussed in Section 2.7.2 Disaster Management Cycle and Resilience Cycle, resilience responses fall into the five different capacities of preventative, anticipative, absorptive, adaptive, and transformative, and solutions within all of these capacities are necessary to build resilience. These operational changes reported by the respondents represented a variety of these capacities, some representing small changes to daily routines, e.g. wearing of masks, while others represented complete restructuring, e.g. planned transformation of the CRR program into a governmentally sponsored program.

In addition to the adaptations indicated by respondents, the recommended CRR-CEE synergies displayed in Figure 23 provide further solutions to lack of financial certainty and to the inability to access field sites, as well as a recommendation to address damaging fishing practices caused by community food and financial insecurity. While many of these adaptations and recommendations are complex and potentially costly, implemented together they would be able to address nearly every major disrupting factor of COVID-19.
It is also important to note that the dates the survey responses were collected, September 3rd - 14th, were only 5 months after the onset of the pandemic. It is likely, therefore, that the CRR practitioners surveyed are not finished adapting and innovating, and that this study does not fully represent the operational modifications that these programs will make in the future. Additionally, the development of so many and such diverse adaptation/recommendations to a novel event in a five-month time frame is also indicative of a strong ability for these programs, working in tandem with each other and with CEEs, to adapt to future disruptions.
Chapter 5: Conclusions and Recommendations

5.1 Summary of Findings

The impact of the COVID-19 pandemic has extended far beyond human health. Attempting to control the spread of a pandemic broad-sweeping safety were implemented, e.g. government policies of country-wide stay-in-place orders and the closure of borders to international travel. While these protocols are undoubtedly invaluable for combating the spread of COVID-19, they also have majorly disrupted our global society accustomed to nearly unlimited international travel and general freedom to go about our work and lives. This is evidenced in the disruptions CRR programs faced in their restoration work, and by the fact that this University of South Florida thesis on CRR in the TWA was completed entirely in Oklahoma and Pennsylvania.

For this study, 11 TWA CRR practitioners were surveyed on how the COVID-19 pandemic is/has been impacting the CRR program, the reefs they serve, and any operational changes they have made or will make to their program to adapt to COVID-19 and future widespread disruptions. Representing CRR programs in 10 countries/regions, every respondent surveyed reported their CRR program was disrupted by COVID-19, although only six respondents (55%) reported their community having had any confirmed COVID-19 cases. The most commonly disrupted CRR activities were data collection and analysis, and all aspects of field work including outplanting, donor fragment collection, nursery and outplant site monitoring and maintenance, and nursery and outplant site identification and development. CRR programs also experienced significant disruption to educational and community outreach.
The most indicated causes of these disruptions fell into the categories of lack of financial certainty, lack of reliable workforce, and inability to access field sites, except for the fear of personally contracting COVID-19, which was the second most cited cause of disruption. An operational change to address these categories was reported by at least one respondent for each, although three respondents did not report any operational changes. Respondents reported implementing COVID-19 prevention tactics – e.g. masks, social distancing, non-rotating dive teams, mandatory disinfection – to address the fear of contracting COVID-19. To address the lack of financial certainty, one respondent reported plans to restructure their program as a governmental program to secure an annual budget, while others reported plans to diversify funding. To address the lack of a reliable workforce, one respondent reported plans to increase their program’s local workforce, and one reported performing their program’s field work themselves. To address inability to access field sites, respondents reported securing special permission to operate from their respective governments, switching from dive trips to snorkeling trips for maintenance and monitoring, and shifting focus from field work to analyzing data and applying for grants. When asked what, if anything, their program needed to continue their restoration work throughout the duration of the pandemic, the respondents most commonly mentioned funding and a reliable, healthy workforce.

Nine of the eleven respondents noted changes to the health of the reefs that their program serves during the COVID pandemic. While two noted coral health was overall good or even improved, possibly due to a decrease in human use of the reef and reef-adjacent areas following the decline of tourism, the remaining seven respondents noted either corals succumbing to the “coral pandemic” of SCTLD or damage to the reef ecosystem in the form of diminished fish populations. This decrease in fish was linked to an increase in fishing, much of which employed
techniques that are damaging to the reef structure. This study hypothesizes this increase in reef fishing is linked to loss of livelihood and food insecurity within reef adjacent communities due to COVID-19 pandemic motivated government policies.

This study proposes three ways Civil and Environmental Engineers (CEE) can assist CRR practitioners in building resilience to future widespread disruptions into their programs: 1) develop remote monitoring systems for both in-situ and ex-situ restoration sites, 2) assess FEW network of reef-adjacent community(ies) to identify opportunities to strengthen local food systems, and 3) partner with CRR programs to develop NbS, integrating CRR with coastal storm/erosion protection objectives to procure reliable funding from governments and the private-sector.

The COVID-19 pandemic and the resulting disruptions to human systems has, as one respondent stated, only reinforced the value of healthy reefs in “providing food security and economic benefits, recreational activities, and coastal protection.” While this thesis is a case study of the COVID-19 pandemic, its findings have implications beyond this single event. Many of the major disrupting factors indicated in this study - such as decreases in tourism, inability to access site(s), and financial uncertainty are likely to occur in other major disruption events, such as war, economic crisis, or natural disaster. Many projections predict that disruptions on the scale of COVID-19, both pandemics and other disasters, are to become more frequent in the coming century (Collins et al., 2019; K. F. Smith et al., 2014). Accordingly, many of the stated adaptation strategies, both those related to CRR practitioners and those recommended for partnership with CEEs, are important to the overall resilience of CRR programs in the face of any major disrupting event. However, local action, or even united action of all CRR programs, will not be enough to preserve coral reefs and the ecosystem services they provide. The stress on
coral reef ecosystems is expected to globally increase as climate change drives ocean warming and ocean acidification, potentially to more than 99% mortality rates is global warming reaches 2°C. (IPCC, 2018). As such, to prevent the mass extinction of corals and the ecosystems they support, it is imperative for the local action of CRR programs and local governments to be paired with global policy to curb greenhouse gas emissions and prevent global warming from exceeding 1.5°C.

5.2 Limitations

While this study gives valuable insight into TWA reefs and CRR programs during COVID-19, it has many limitations. First, this study only collected responses from one respondent per CRR program. While this was useful in that the respondents represented a large sample of CRR projects in several countries, it is likely that these respondents were unable to present a complete picture of how the COVID-19 pandemic was impacting their program and reef sites. Furthermore, the respondents to this study consisted exclusively of program managers, directors, and others of similar titles. While this was beneficial in that respondents of these positions are more likely to know the details of financial loses and planned operational changes, it also is limiting in that it precludes the perspective of a more general coral gardener. Also, many of these respondents were not from the location of their program. This could render them less likely to understand the dynamics of the surrounding communities.

Another study limitation comes from the fact that the data for this study was collected almost exclusively through surveys, where respondents expressed their experiences and views through multiple-choice and open answer questions. As such, the respondents’ claims about, among other things, the health of their reef sites and the number of confirmed COVID-19 cases in the communities their programs serve, have not been verified. Moreover, as the results of this
study were compiled and reported without reconfirmation with the respondents, it is possible that some responses were misunderstood and/or misrepresented in this study. However, this study intentionally did not report any respondent as expressing anything they did not explicitly state in either a multiple choice or open answer response. Any extrapolation of these responses is indicated as such.

5.3 Future Research

This study lends itself to future research. One possible project would be to repeat this study using the same survey, but target coral local diver masters, fisherpersons, and others employed as coral gardeners by these CRR programs. Amassing the experiences of these CRR practitioners would give further insight into the impact of COVID-19 on CRR programs. Comparing these responses with this study of CRR project managers could lead to the discovery of important differences in the experiences of these two groups.

Future extensions of this research could also include a follow-up study of these same CRR programs after the cessation of the COVID-19 pandemic. It could evaluate the productivity levels of the programs and compare them to past productivity level before and amidst the COVID-19 pandemic. Research could also look at changes implemented to the programs as a result of experience with the COVID-19 pandemic, and how these changes are impacting the overall productivity, operation structure, and scope of the programs. It would also be interesting to survey the communities the CRR programs serve to better understand their relationship with the reef sites during COVID-19, and if their experiences of the pandemic altered their perceptions of or interactions with the reef sites.

Possible future engineering research includes the development of remote monitoring systems for in-situ and ex-situ nurseries and in-situ outplant sites. Special opportunity exists in
the development of such remote monitoring systems to be developed for operation by local stakeholders within the reef adjacent communities. Other research could include mapping the food-energy-water nexus of a community adjacent to a reef experiencing an increase in fishing amid the COVID-19 pandemic to discover leverage points to encourage more sustainable fishing practices. Finally, future research could include working with CRR practitioners on a project to develop a CRR program following an NbS ridge to reef framework to simultaneously restore ecosystem health and strengthen coastal infrastructure.
References


CCRIF. (2010). *CCRIF’s Economics of Climate Adaptation (ECA) Initiative ... preliminary results of the ECA Study.*
https://www.ccrif.org/sites/default/files/publications/ECABrochureFinalAugust182010.pdf

Center for Disease Control. (2020). *Coronavirus Disease 2019 (COVID-19) | CDC.*

https://doi.org/10.1016/j.jembe.2011.02.025


https://doi.org/10.1126/sciadv.aax9395

https://doi.org/10.1016/j.ecoser.2012.07.005


EXEMPT DETERMINATION

July 14, 2020

Linden Cheek
303 NW Palomino St
Bentonville, AR 72712

Dear Linden Cheek:

On 7/13/2020, the IRB reviewed and approved the following protocol:

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<td>Review Type</td>
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<td>Title</td>
<td>Comparative Resilience to COVID-19 of Coral Reef Restoration Operations in the Caribbean and Florida Keys</td>
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<td>University of South Florida</td>
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<td>Protocol</td>
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The IRB determined that this protocol meets the criteria for exemption from IRB review.

In conducting this protocol, you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Please note, as per USF policy, once the exempt determination is made, the application is closed in BuildIRB. This does not limit your ability to conduct the research. Any proposed or anticipated change to the study design that was previously declared exempt from IRB oversight must be submitted to the IRB as a new study prior to initiation of the change. However, administrative changes, including changes in research personnel, do not warrant a modification or new application.

Ongoing IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities impact the exempt determination, please submit a new request to the IRB for a determination.

Sincerely,

Jennifer Walker
IRB Research Compliance Administrator
Appendix B: TWA CRR Practitioner Survey Questions
Coral Reef Restoration in the West Atlantic amid COVID-19

Q1 Informed Consent to Participate in Research

Information to Consider Before Taking Part in this Research Study

**Title:** Comparative Resilience to COVID-19 of Coral Reef Restoration Operations in the Caribbean and Florida

**KeysStudy #** _001053__________

**Study Staff:** This study is being led by Linden Cheek who is a Master’s of Civil and Environmental Engineering candidate at the University of South Florida, Tampa. This person is called the Principal Investigator. She is being guided in this research by Dr. Rebecca Zarger of Applied Anthropology and Dr. Maya Trotz of Civil and Environmental Engineering. Other approved research staff may act on behalf of the Principal Investigator.

**Overview:** You are being asked to take part in a research study. The information in this document should help you to decide if you would like to participate. The sections in this Overview provide the basic information about the study. More detailed information is provided in the remainder of the document.

**Study Details:** This study is being conducted at the University of South Florida, Tampa. The purpose of the study is to explore the impact of the global COVID-19 pandemic on coral reef restoration programs in the West Atlantic and Caribbean. It will examine how different programs in different locations have been impacted by the virus and its disruption to global, national, and local human systems. It will seek to determine what major factors have allowed coral reef restoration operations to continue and what factors have caused these restoration operations to decrease or stop altogether. It will also explore how the COVID-19 pandemic has affected human perception of coral reef restoration and its role in communities. The research will primarily be carried out through a 15-minute questionnaire. You will have the option at the end of the questionnaire to volunteer as a key-informant for a 30-minute follow-up interview.

**Participants:** You are being asked to take part because you are a primary staff member of a coral reef restoration program in the Florida-Caribbean region. You have been directly involved in coral reef restoration at your site both before and during the COVID-19 pandemic and, therefore, we believe that you are able to accurately assess the state of your program’s operations before and after the onset of the pandemic.

**Voluntary Participation:** Your participation is voluntary. You do not have to participate and may stop your participation at any time. There will be no penalties or loss of benefits or opportunities if you do not participate or decide to stop once you start.

**Benefits, Compensation, and Risk:** We do not know if you will receive any benefit from your participation. There is no cost to participate. You will not be compensated for your participation. This research is considered minimal risk. Minimal risk means that study risks are the same as the risks you face in daily life.

**Confidentiality:** Even if we publish the findings from this study, we will keep your study information private and confidential. Anyone with the authority to look at your records must keep them confident. Privacy: It is possible, although unlikely, that unauthorized individuals could gain access to your responses because you are responding online. Confidentiality will be maintained to the degree permitted by the technology used. No guarantees can be made regarding the interception of data sent via the Internet. However, your participation in this online survey involves risks similar to a person’s everyday use of the Internet. If you complete and submit an anonymous survey and later request your data be withdrawn, this may or may not be possible as the researcher may be unable to extract anonymous data from the database.

We may publish what we learn from this study. If we do, we will not let anyone know your name. We will not publish anything else that would let people know who you are. You can print a copy of this consent form for your records.

Contact Information: If you have any questions, concerns or complaints about this study, call Linden Cheek at 479-256-9112 or email her at linde3@usf.edu. If you have questions about your rights, complaints, or issues as a person taking part in this study, call the USF IRB at (813) 974-5638 or contact the IRB by email at RSCH-IRB@usf.edu.
Q2 It is up to you to decide whether you want to take part in this “minimal risk” study. If you complete and submit the online survey, you are agreeing to take part in research. If you volunteer to serve as a key-informant in a follow-up interview, you will have the opportunity to review your consent before the interview. I freely give my consent to take part in this study. I understand that by proceeding with this survey, I am agreeing to take part in research and I am 18 years of age.

- Yes, I freely consent to take part in this study
- No, I do not consent to take part in this study

Q3 In your opinion, when did the disruption caused by COVID-19 first begin impacting the community of the coral reef restoration program you work for? (If you do not believe the disruption caused by COVID-19 has impacted your community, please write NONE)

Q4 Please briefly describe the restoration program you work for.

Q5 How has your program traditionally funded projects before the COVID-19 pandemic? Select all that apply.

- Competitive Grant
- National government loans/funds
- Foreign government loans/funds
- Donation
- Fees
- Private Partnership
- Other
- Unsure
- None

Q6 What other sources has your program traditionally used for funding before the COVID-19 pandemic?

Q7 Has funding for the coral reef restoration program you work for been impacted by the COVID-19 pandemic?

- Yes
- No
- Unsure

Q8 Please describe how funding has been impacted by COVID-19 pandemic:

Q9 Have any people in the communities that your coral reef restoration project serves tested positive for COVID-19?

- Yes
- No
- Unsure
Q10 OPTIONAL: Please estimate how many people in the community of your coral reef restoration project have tested positive for COVID-19?

- o 1-10
- o 11-49
- o 50-99
- o 100-499
- o 500+

Q11 How has COVID-19 impacted your program's ability to employ workers? Compare how many workers your program currently employs versus what your program expected to employ prior to COVID-19.

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<tr>
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Q12 Since COVID-19 began impacting the reef restoration program you work for, has your program experienced disruption to any of the following? (select all that apply)

- o Collecting donor fragments
- o Monitoring of coral nurseries
- o Nursery maintenance
- o Monitoring of reef restoration or other reef sites
- o Restoration site management
- o Maintenance of boats or gear/equipment
- o Buying gear/equipment (for example: SCUBA gear, tank refills, tools)
- o Outplanting
- o Identification of new nursery sites
- o Development of new nursery sites
- o Identification of new outplanting sites
- o Development of new outplanting sites
Q13 Please describe what other disruptions your program has faced:

Q14 If you have noticed any change(s) in the surrounding community's opinion of your reef restoration site(s) since COVID-19 began to impact the community, please describe the change(s) below:

Q15 If you have noticed any change(s) in the human use/interaction with your reef restoration site(s) since COVID-19 began to impact the community (these could include changes in tourist use, changes in community fishing behaviors, etc.), please describe the change(s) below:

Q16 If you have noticed any change(s) in the coral reef ecosystem of your reef restoration site(s) since COVID-19 began to impact the community (these could include fish abundance and type, algal abundance, coral health, etc.), please describe the change(s) below:

Q17 Please select which of the following, if any, have made it difficult for you and the other workers at your program to maintain regular restoration work during the COVID-19 pandemic. Please only select answers that have been aggravated by COVID-19 related disruptions. Do not select any answers if your program has not experienced disruption due to the COVID-19 pandemic.

Q18 Basic Needs
- Difficulty accessing food
- Difficulty accessing clean water
- Difficulty accessing fuel
- Difficulty accessing power
- Difficulty accessing transportation
- Difficulty accessing shelter
- Difficulty accessing gear/equipment
- Difficulty accessing internet

Q19 Government Protocols
- Stay-in-place orders
- Government mandated shutdown of reef restoration operations
- Government mandated curfew

Q20 Money
- Lack of funding (for the operation)
- Lack of income (for the employees)
- Employees needing to seek other employment
- Uncertainty about future funding
- Increase in cost of maintaining operation
Q21 Health
- Lack of access to medical care
- Sick with COVID-19
- Fear of personally getting sick with COVID-19

Q22 Family and Community
- Fear of passing COVID-19 to family member or friend
- Family obligations (caused or increased by COVID-19)
- Lack of community support
- Improper use of reefs by community
- Improper use of reefs by reef restoration workers

Q23 Tourism
- Lack of tourist volunteers
- Lack of fees from tourists

Q24 Other

Q25 If the disruption caused by COVID-19 made you unable to continue your regular reef work, how long were you unable to perform this work up to this point in time?
   Estimated number of days unable to work ____________________________

Q26 If your program has made any operational changes to respond to COVID-19 to date, please describe. (If you do not know, please write "do not know")

Q27 If your program is planning on making any future operational changes based on your experience with COVID-19 to date, please describe. (If you do not know, please write "do not know")
Q28 How effectively do you think the community accessing or surrounding your coral reef restoration site(s) was able to adjust to the disruption caused by COVID-19? (0 = not at all effective, 5 = completely effective)
Fill in the stars to give your rating

Q29 How effectively do you think your coral reef restoration program was able to adjust to the disruption caused by COVID-19? (0 = not at all effective, 5 = completely effective)
Fill in the stars to give your rating

Q30 Is the coral reef restoration program you work for currently able to perform some or all of its planned work?
  o Yes, all
  o Yes, some
  o No
  o Do not know

Q31 Do you believe that your program will be able to operate through the end of the disruptions caused by the COVID-19 pandemic?
  o Definitely yes
  o Probably yes
  o Might or might not
  o Probably not
  o Definitely not
  o Do not know

Q32 When the disruptions caused by the COVID-19 pandemic are over, how well do you think your program will be performing compared to the same time of year before the pandemic began?
  o Much better
  o Somewhat better
  o About the same
  o Somewhat worse
  o Much worse

Q33 What, if anything, do you think your program needs to enable you to continue your restoration work during this pandemic?
Q34 How important do you think it is for your restoration program to continue its work during this pandemic?

- Extremely important
- Very important
- Moderately important
- Slightly important
- Not at all important

Q35 In your own words, please explain why you believe this:

Q36 Please provide some more information about yourself. This information will not be shared in any way that would identify you with this survey and your anonymity will be maintained.

- Gender ________________________________
- Nationality ________________________________
- Country in which your reef restoration program works __________________________
- Your role within the program __________________________
- How long you have worked for this program __________________________

Q37 Would you like to volunteer to serve as a key informant by participating in a 15 to 30-minute follow-up interview? *This interview can take place either as a phone call or video chat.*

- Yes
- No

Q38 Please provide an email address or WhatsApp number you would like to be contacted with to set up an interview.
Appendix C: Survey Recruitment Email

Dear (CRR practitioner name),

My name is Linden Cheek and I am a Master’s student in the Department of Civil and Environmental Engineering at the University of South Florida. I am currently working on a study to be completed this Fall, IRB #001053: *Comparative Resilience to COVID-19 of Coral Reef Restoration Operations in Florida and the Caribbean*.

The study aims to explore the effect of the COVID-19 global pandemic on coral reef restoration programs in the West Atlantic. It is concerned with 3 major questions:

1. What effects, if any, has the disruption caused by COVID-19 had on coral reef restoration programs?
2. What effects, if any, has the disruption caused by COVID-19 had on the coral reef ecosystems maintained/monitored by these reef restoration programs?
3. How have reef restoration programs, both as individuals and organizations, been resilient to and responded to these disruptions?

Dr. Maya Trotz, who is advising this study, recommend your organization as an important program to be included in this study. We believe it is important to learn how you and other reef restoration workers are responding to the COVID-19 disruption to share best-practice responses and better design resilience into reef restoration programs for the future.

To take part in the study, all you need to do is fill out a 15-minute electronic survey, [usf.reefrestorationCOVID.survey.com]found at this link. The link to the survey is also at the bottom of this email. The survey will ask questions about your restoration program, how you have noticed the COVID-19 pandemic effecting the program and the reef, and any steps your organization has taken/plans to take in response. There is also an opportunity at the end of the survey to volunteer as a key informant for a 30-minute follow-up phone or video interview.

The three requirements to participate in the survey are to be 18 years or older AND a current worker at your coral reef restoration organization AND have worked there for at least one year. Please forward this email to anyone else in your organization that meets these requirements and is interested in giving their input in this study.
Access to this survey will close on September 12\textsuperscript{th}. Please make sure to complete your submission before then.
Thank you for your time. My research team and I look forward to gathering your perspective on the unprecedented situation of maintaining coral reef restoration work amid a global pandemic. We believe your work is important and hope to document your experience of this disruption in a way that empowers future reef restoration work in the West Atlantic and beyond.

Sincerely,  Linden Cheek  
Civil and Environmental Engineering Master’s Candidate  
University of South Florida  
Tampa, FL  
Li LINK TO SURVEY:  LINK CLOSES SEPTEMBER 14TH
Appendix D: Copyright Permissions

The permission below is for the use of Figure 5

Re: Request to use Figure 2 from Re-evaluating the health of coral reef communities in Master's Thesis

Yes, no problem and best of luck!

Jennifer

On 10/19/2020 11:13 AM, Cheek, Linden wrote:

Good afternoon Dr. Smith,

I am writing to follow up on a previous email I sent you requesting to use a Figure from your paper Re-evaluating the health of coral reef communities: baselines and evidence for human impacts across the central Pacific in my Master’s thesis. have you been able to review my request and decide if I can use this figure?

Thank you for your consideration,
Linden Cheek

From: Cheek, Linden
Sent: Tuesday, October 13, 2020 12:10 PM
To: jsmith3@ucsd.edu; js0013@ucsd.edu
Subject: Request to use Figure 2 from Re-evaluating the health of coral reef communities in Master's Thesis

Dear Dr. Smith,

My name is Linden Cheek. I am PhD student in Civil and Environmental engineering at the University of South Florida working under Dr. Maya Trotz. I am completing my Master’s along the way and the topic of my thesis is Coral Reef Restoration in the Tropical West Atlantic amid COVID-19.

In my lit review I have section where I discuss phase-shifts from coral to algal dominated reefs. I would like to use Figure 2 from your paper Re-evaluating the health of coral reef communities: baselines and evidence for human impacts across the central Pacific as an illustration of this phenomenon. I am aware that this paper addresses the central pacific, and not the west Atlantic, but I still believe this figure does an excellent job of illustrating phase-shifts.

May I have permission to use your figure in my thesis? If so, how would you like for me to credit you and your colleagues?

Thank you for your time,
Linden Cheek

---

Jennifer E. Smith
Professor, Marine Biology
Scripps Institution of Oceanography, UCSD
Office: (858)453-0530
Email: smithj@ucsd.edu
Lab Website: https://scripps.ucsd.edu/labs/occaireefecology/
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Nov 10, 2020

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