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Spatial Analysis of Environmental Factors Affecting Endangered and Invasive Fish Species on the Belize Barrier Reef

Adam S. Acker

SPATIAL ANALYSIS OF ENVIRONMENTAL FACTORS AFFECTING ENDANGERED AND INVASIVE FISH SPECIES ON THE BELIZE BARRIER REEF

by

ADAM ACKER

Under the Direction of Christy C. Visaggi, Ph.D. and Timothy L. Hawthorne, Ph.D.

ABSTRACT

The second largest reef in the world is experiencing a dramatic change in its environment with continued development and an influx in tourism having a direct impact on the physical and ecological balance of the reef. The introduction of hazardous materials and practices have contributed to reef degradation through excess sedimentation, overfishing, and increased shipping and have the ability to influence some of the reef's most endangered inhabitants. A spatial examination using multiple variables impacting changes in certain populations of endangered and invasive fish species are studied, incorporating integrated species abundance and sighting data as well as potential environmental threats to aim to understand the trends and correlations between Belize's recent spike in development, and the implications on its barrier reef.

INDEX WORDS: Belize, Barrier reef, GIS, Invasive, Endangered, Environmental threat

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ADAM ACKER

Committee Chair: Christy C. Visaggi

Co-Chair: Timothy L. Hawthorne

Committee: Jeremy E. Diem

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1 INTRODUCTION

Less than 1% of the world is comprised of coral reef, with nearly 25% of the biodiversity in the ocean calling reefs home (Cerullo & Rotman, 1996), yet across the spectrum, the degradation of coral reefs and their inhabitants are at an all-time high due to recent anthropogenic influences on reef environments across the globe (Pandolfi et al., 2003). The direct correlation of the health of reefs due a rise in both natural and human induced factors can be seen in the fluctuation in some of its most important fish species, exhibiting the most noticeable impacts to the largest reef systems such as the Great Barrier Reef in Australia and Mesoamerican Reef stretching down the coast of Central America (Perkins & Carr III, 1985). Negligent practices and environmental hazards have the ability to disrupt the delicate geologic and ecological balance of a reef structure (Maidens & Burke, 2005). Fish species of reef habitats are particularly vulnerable to change even on the smallest of scales (Williams et al., 2011). Correlating the characteristics and traits of certain threatened or invasive fish could provide an outline of what is happening around them. Acting as indicator species, inhabitants of a given ecosystem are the greatest storytellers (Fenner, 2014).

Although research studying fish distributions as related to environmental factors has been done in other settings (e.g., Pittman & Brown, 2011), each reef system in the world is different and comes with its own set of ecological dynamics (Cerullo & Rotman, 1996). Each potential stressor must be understood in order to create management plans for future sustainability (Bellwood et al., 2004). The influx of growth and development in larger, more pressured barrier reef systems has come in a relatively short period of time, and while there are ongoing studies examining the effects of such habitat changes, research that explicitly integrates data on fish and environmental variables is needed. The large scale remnants of the negative effects occurring on reefs were not substantially considered until fish, a major source of industry, were reaping the unfortunate cost of the growing economy and all that it entails (Babcock, et al., 2013). This study examines multiple variables that might impact changes in certain populations of fish by examining integrated sighting and abundance data as well as potential threats through Geographic Information Systems (GIS) mapping across space and time.

For the purpose of this study, the Mesoamerican Reef system, and the Belize Barrier Reef in particular will act as the study setting that will be assessed spatially using its invasive and threatened species therein and looking into environmental threats that affect coral reef systems throughout the world. The Healthy Reefs for Healthy People initiative recently gave the Mesoamerican Reef a Health Index score of fair (2.8) on a scale of five noting a continued history of declining fish populations as part of the problem (ICRI, 2015). The Belize Barrier Reef acts as a good model to study fish species indicative of reef health due to the country's recent increase in growth and development largely from the tourism industry surrounding the barrier reef (Arkema et al., 2014). This work aims to create a research structure incorporating multiple datasets specific to Belize with an approach that can be applied to reef systems around the world in an attempt to identify relationships between environmental threats that may lead to wide scale degradation on a given coral reef and the impact of such factors on its inhabitants.

The introduction of hazardous materials and practices have contributed to reef degradation through excess sedimentation, overfishing, and increased shipping which can all lead to a disruption in the geologic and ecological balance of the barrier reef in Belize (Maidens & Burke, 2005). GIS will act as the platform to investigate the spatial distributions of fish species across time and their relationship to impacts and sustainability efforts associated with threats to the Belize Barrier Reef. The very species that have thrived within a portion of the Mesoamerican Reef for hundreds of thousands years are shifting their practices, fluctuating in numbers, and are now under the spotlight due to changes to their environment, so why not use them to uncover the true impact a rise in economy has beneath the water?

1.1 Research Objectives

A series of objectives pertaining to a broader research question will provide the basis for the route in which the research topic is addressed. The question and subsequent objectives are as follows:

How do at risk and invasive fish populations vary in space and time as related to environmental threats on the Belize Barrier Reef?

- Objective 1: Analyze the sighting frequency and abundance of fish species in space and time
- Objective 2: Examine the spatial relationship of fish species to modeled environmental threats
- Objective 3: Assess the effectiveness of marine protected areas in relation to fish abundances and distribution
- Objective 4: Investigate the timing and spread of the invasive Red Lionfish

1.2 Study Area

The Belize Barrier Reef makes up a substantial segment of the Mesoamerican Reef in the Caribbean Basin, which is renowned as the second largest coral reef system in the world. The reef hugs the coastline of Belize, stretching nearly 190 miles, and comprising nearly 370 square miles (Maidens & Burke, 2005). The country of Belize and its barrier reef are a rapidly expanding tourist attraction that has come with a cost. As a leading economic source of income, the commercialization and increase in new potentially harmful sources being introduced to the reef is causing a change in not only the physical properties but the biodiversity as well. The fish species deemed as threatened and invasive are of particular importance, as they act as key indicator species to the overall health of the reef (The Directory of Belize's Protected Areas, 2011). The unique geology and environments encompassed within the Belize Barrier Reef have been stable for thousands of years (Gischler & Hudson, 2004), yet the exponential influx of new changes to the environment are causing a rapid decline in the overall well-being of the reef as a whole (Copper, 1994). Understanding the importance of the impact each individual potential hazard has across time on the environment and to the fish species in concern will be the key to identifying the impact this recent growth in development is having on one of the world's largest reefs.

The study area will encompass all the barrier reef system stretching from north to south, as well as the outer reefs and atolls in Belize. The entire stretch of reef, both closest to the shore as well as the atolls and outer reefs experience development and encompass major tourist destinations that are becoming increasing commercialized (Maidens & Burke, 2005). The main three habitats of importance to this study are seagrass, mangroves, and coral reefs, which are further broken up into patch, shallow, and spur and groove reefs (Figure 1). These habitats are the foundation for biodiversity on the barrier reef system. Although the coral reef is the most notably targeted as the center of the ecosystem within the Belize Barrier Reef, seagrass and mangroves are also extremely important to several populations of severely threatened species that are focused on within this research.

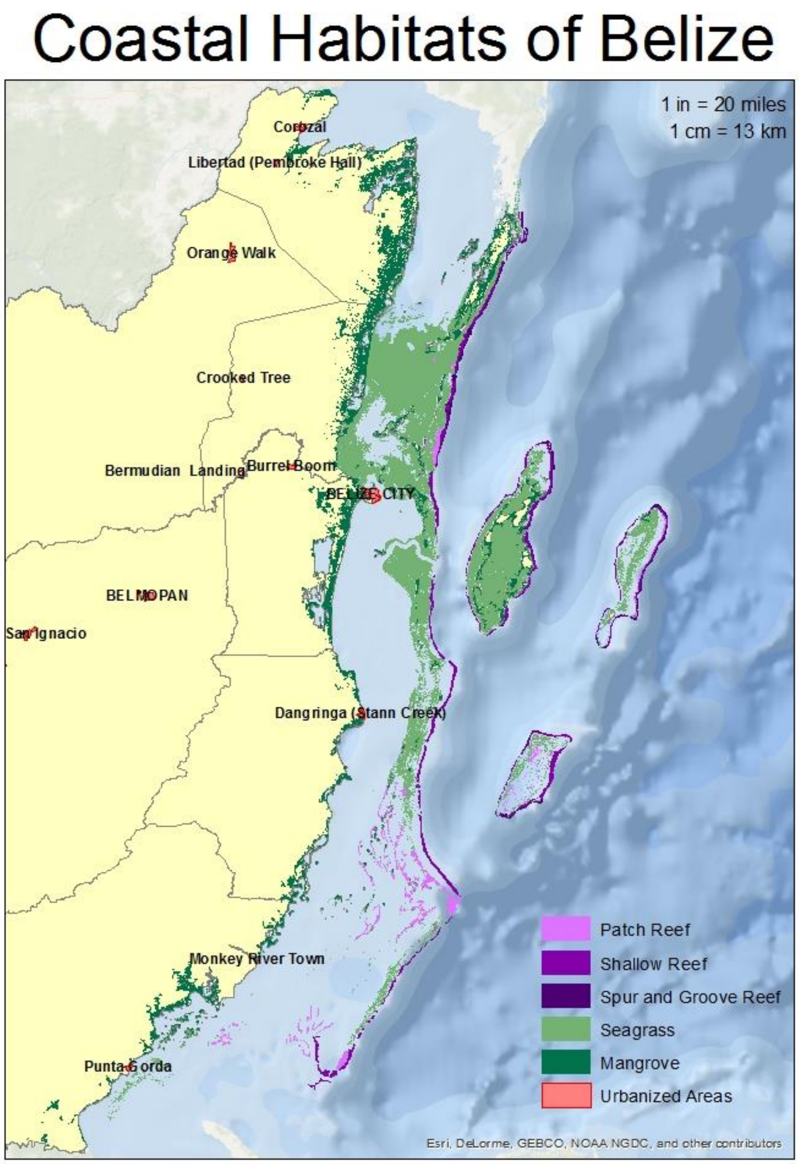

Figure 1: Coastal habitats of Belize (CZMAI)

1.3 Factors Affecting the Reef

Coral reef ecosystems are largely susceptible to both natural and human impacts. The degradation of large coral reef systems has been in effect for centuries and is continually being enhanced with the addition of development and movement around these areas (Pandolfi et al., 2003). With the vast amount of stressors to a reef system as large as the Belize Barrier Reef, several key categories have been identified and modeled by the Belize Coastal Zone Management Authority and Institute (CZMAI) for the Belize Coastal Threat Atlas data produced by the World Resources Institute (WRI) pertaining to the overall degradation of the barrier reef. Modeled threats of sedimentation and runoff, coastal development, and marine-based threats will act as the major threat categorizations to the reef, while implications of overfishing and the impact of the spread of invasive species will also be discussed in relation to the spatial distribution of several at risk species over time. In the case of the Belize Barrier Reef, many of the factors that have the ability inflict an immediate threat to the reef system may have been enhanced by the increase in tourism (Crain et al., 2008). These stressors are increasing in area and over time with the development of Belize's coastline, which can have a negative effect on surrounding habitats if not properly maintained (Samhouri & Levin, 2012). Many of the human-induced threats have the ability to alter both the water chemistry, as well as the physical makeup of the barrier reef aside from directly influencing biota that live in and around reef settings. In a coastal environment, both natural and human induced impacts can be felt from far inland, on the coast itself, as well as in marine-based sources found offshore (Pandolfi et al., 2003).

1.3.1 Sedimentation and Runoff

Sedimentation has become a growing issue with a direct correlation to agricultural runoff near the coast as well as being transported through rivers draining out into the ocean (Maidens & Burke, 2005). Sedimentation from runoff can have a negative effect on the reef nearshore in particular by affecting the sediment load, potentially raising the level of the ocean floor, introducing harmful agricultural chemicals such as fertilizers and pesticides into an environment which can prove to be toxic, and clouding up the water making it difficult for some biota to live

(McCloskey & Liu, 2013). Figure 2 and 3 show the sedimentation and runoff threats that were mapped from the CZMAI data in the Belize Coastal Threat Atlas. A shallow water marine environment such as the Mesoamerican Reef and Belize Barrier Reef within is particularly vulnerable to sedimentation having an immediate effect on the landscape and its inhabitants (Copper, 1994; McCloskey & Liu, 2013). Many species of fish that reside in reef systems not only in Belize, but throughout the world, rely on shallow hard bottoms such as seagrass and mangrove roots to spawn and reproduce (Bijoux et al., 2013). A recent study conducted by McCloskey and Liu (2013) focused on the sedimentary history of Mangrove Cays in the Turneffe Islands of Belize found that new carbonate sedimentation up to two meters thick is building up on the seafloor. This change is of particular importance because with the depletion of areas in which various fish species spawn, comes a potential lack of reproduction, or a lower survival rate of eggs laid within these ecosystems under the threat of over sedimentation (Williams et al., 2011). Areas of specific importance are focused around mainland runoff sources from farming, as well as the estuaries yielding high sediment loads into the ocean (Maidens & Burke., 2005).

Similar to sedimentation, runoff is a particular source of concern with the majority of today's popular shallow water environments and their diverse species having to deal with the introduction of potentially harmful pollutants or chemicals into the water (Maidens & Burke, 2005). The largest of these concerns in Central American countries, as well as developing countries in particular, are the threats posed by agricultural runoff that can lead to eutrophication and the contribution of excess nutrients resulting in the potential for algal blooms (Samhouri & Levin, 2012). Watershed drainage with connections to agricultural practices has the ability to introduce potentially harmful chemicals, pollutants, and toxins through pesticides and fertilizers, as well as increase the sediment load being deposited in the shallow water reef environment (Arkema et al., 2014). Although invisible to humans, these pesticides and fertilizers have a direct impact on the reef's inhabitants (Samhouri & Levin, 2012). Certain grouper and snapper species in particular are vulnerable to changes within the water chemistry (Patterson et al., 1999; Granados-Dieseldorff et al., 2013), and can act as an indicator to subtle changes in reef settings not picked up by humans.

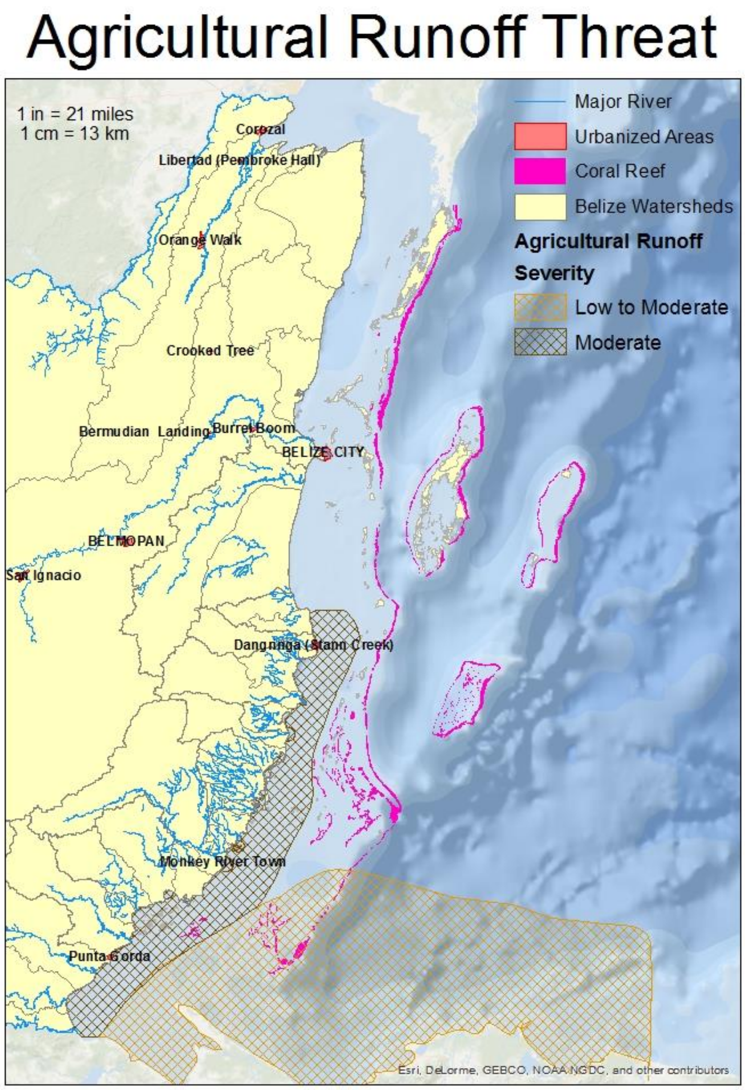

Figure 2: Agricultural runoff threat (CZMAI)

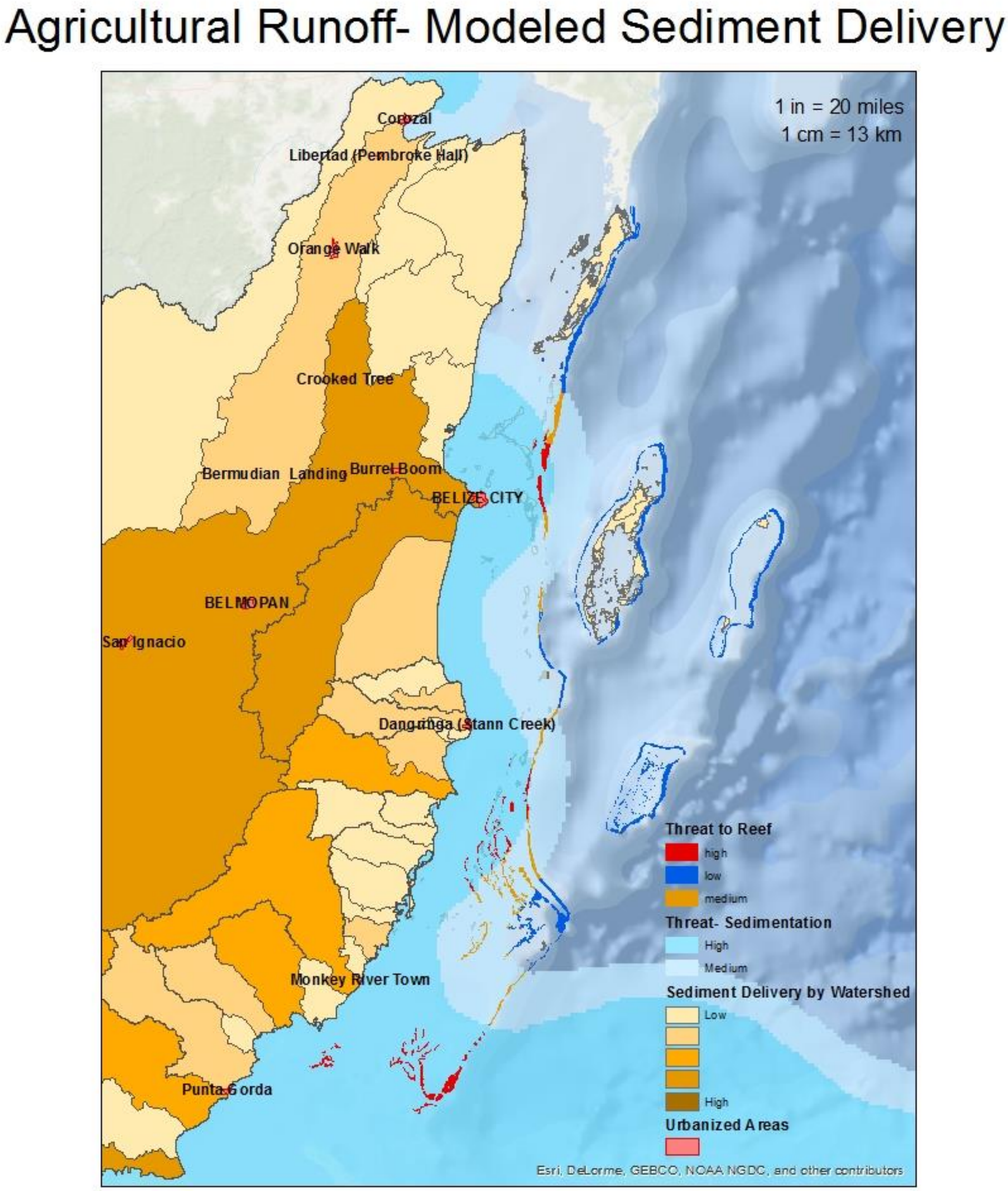

Figure 3: Modeled sediment delivery from agricultural runoff (CZMAI)

1.3.2 Coastal Development

Coastal development has been a primary concern with the increasing popularity of reefs as a tourist destination. While attempting to accommodate for the growing economic boom Belize is experiencing in relation to the reef's tourism draw, building projects, docks, and alterations to natural shorelines have had a major influence on the coastal landscape (Nyström et al., 2008). During coastal development, removal of the underlying landscape, bedrock, and seagrass and mangrove habitats alters the sediment and erosional properties of the coast (Samhouri & Levin, 2012; McCloskey & Liu, 2013). Seagrass and mangroves in particular act to stabilize shorelines, trap sediment, and filter pollutants. Removal of the vegetation loosens the sediment and adversely alters the substrate, allowing the shoreline to be much more easily eroded (Diedrich, 2007). The development can also alter natural drainage patterns, resulting in new materials, sediment, and runoff being deposited in the reef (Maidens & Burke, 2005). The threat posed by coastal development often overlaps with sections of the reef in close proximity to land. These areas often are more susceptible in impacting fish species and the coral reef ecosystem as a whole by affecting nursery grounds and adjacent portions of the reef. All mapped threat models based off of CZMAI data (Figures 4 and 5).

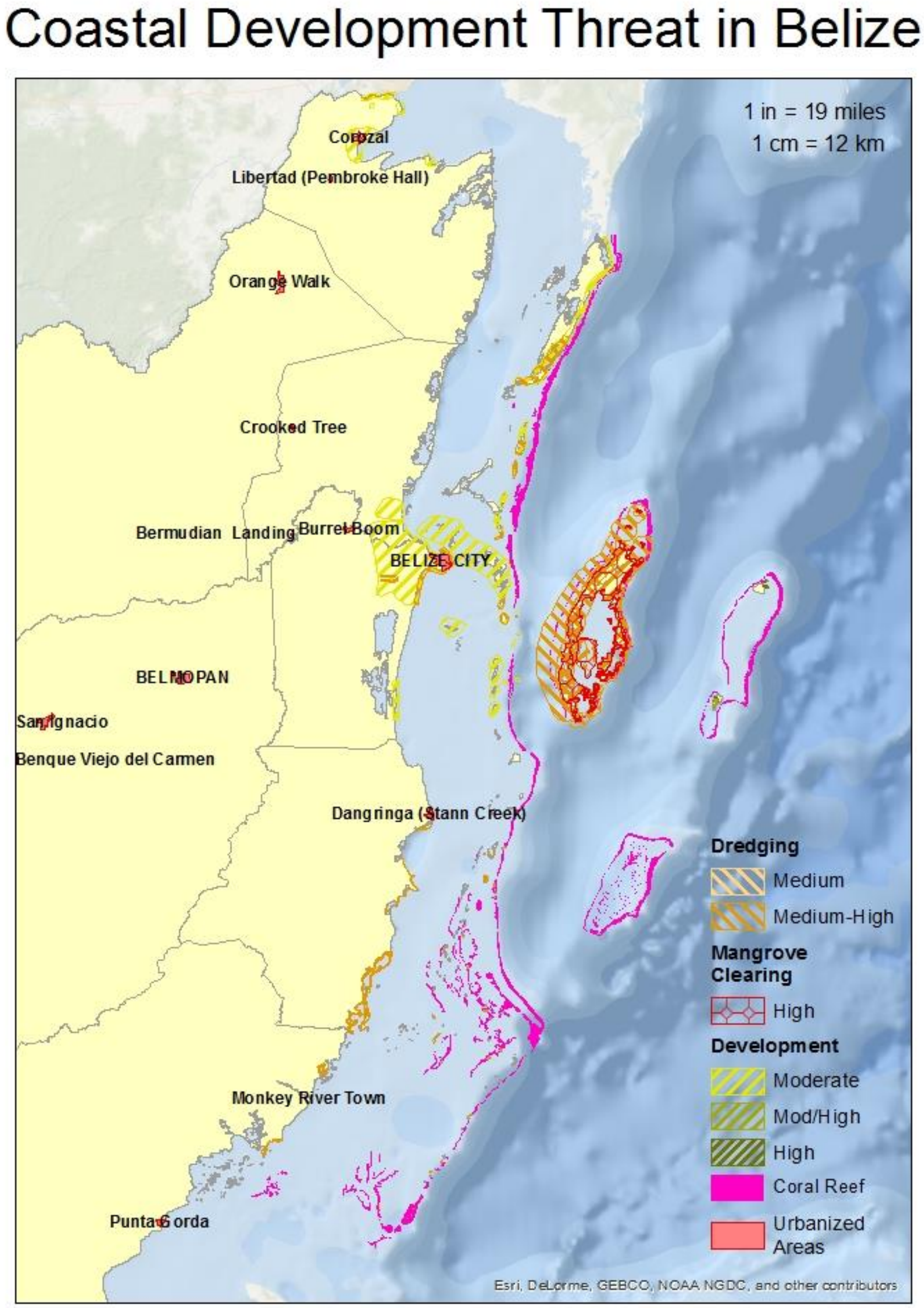

Figure 4: Coastal development threat by practice and severity (CZMAI)

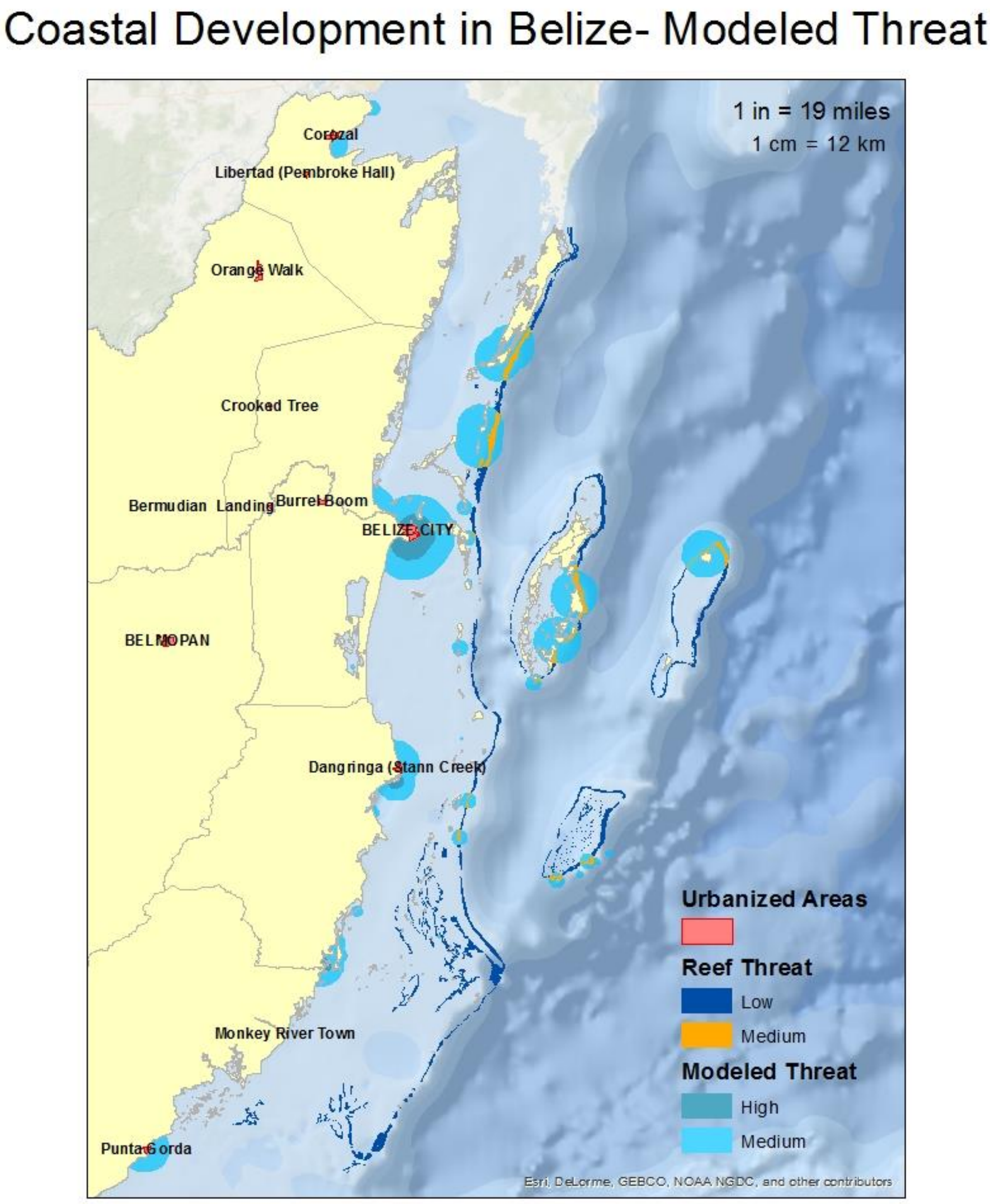

Figure 5: Coastal development modeled threat in Belize (CZMAI)

1.3.3 Marine-Based

Marine-based threats can stem from a variety of different sources within the barrier reef, of which Figure 6 gives a modeled view of the severity based on CZMAI datasets obtained from the most recently published Belize Coastal Threat Atlas. Marine-based threats include possible chemical and physical threats to the reef posed by shipping and ports in which commercial and cruise based shipping operations are conducted. Both dredging channels for large commercial ships as well as pollution and waste being dumped into the ocean via the increased number of boats using shipping lanes throughout the reef are of primary concern.

The bathymetry of a shallow water reef environment such as the Mesoamerican Reef, varies from a few meters deep to around 50 meters deep at the most (Maidens & Burke, 2005). Dredging to accommodate for commercial shipping and importing and exporting goods can be a major concern in such large interconnected expanses of reef that impact the ecology drastically when one part is altered. Dredging to create shipping channels or for other development reasons can result in scars left in the ocean floor from the use of large anchors as well as physically moving sediment to create a deeper channel to accommodate large ships. Mangroves, seagrass, and nearby reefs, which are used as spawning grounds or habitat for fish species, inevitably suffer as a part of the adverse effects of dredging (Maidens & Burke, 2005; Diedrich, 2010; Huntington et al., 2010). Once the ship channels are dredged out and become actively used, new threats from the ships such as spills, discharge, pollution, and dumping of waste become a hazard to the environment as well (Maidens & Burke, 2005; Diedrich, 2010).

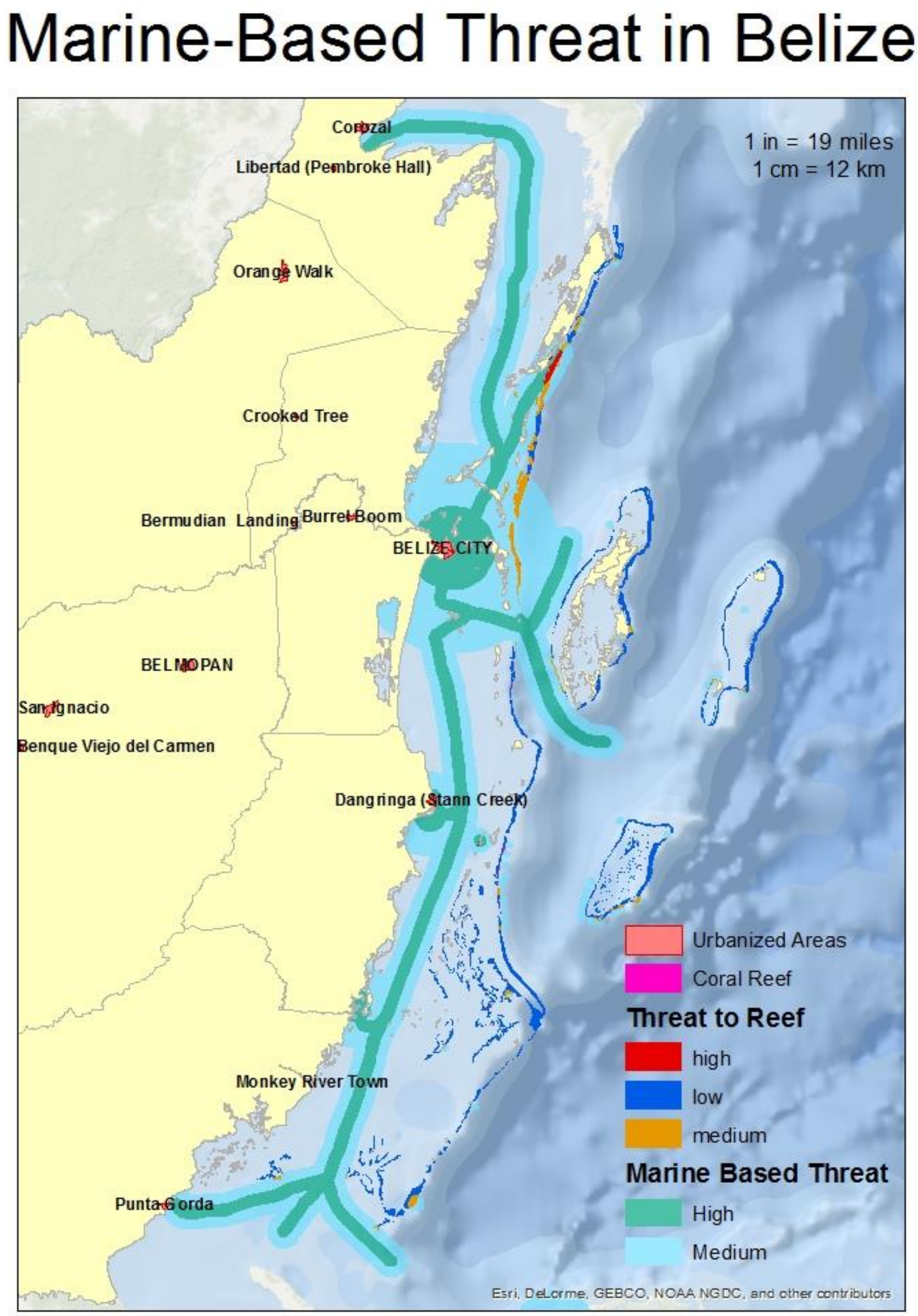

Figure 6: Modeled marine-based threat in Belize (CZMAI)

1.3.4 Overfishing

Throughout the world, one of the largest concerns with the decline in reef species is overfishing, by-catch, and commercial abuse (Fenner, 2014). It is no coincidence that many of the species considered threatened are prized game fish. However, not all threatened species fall under this category; other fish act not as game fish, but serve as smaller indicator species critical to the ecosystem, yet vulnerable to slight changes in their environment. For example, Cox et al. (2013) discusses how the illegal harvest or overfishing practices of herbivorous fish can be one of the most devastating to coral reefs due to the negative impact it has on the overall life cycle of fish species, as well as vegetation and coral. In particular, such fish are often regarded as critical in keeping algal cover to a minimum so that corals can continue to expand in providing new reef structure of biological and geological importance to this setting. Despite marine protected areas being implemented along various reefs within the Mesoamerican Reef (The Directory of Belize's Protected Areas, 2011) fish numbers in many areas, protected or not, are in a gradual decline (Perez, 2009; ICRI, 2015). The guidelines are vague in the designated protected areas, and the results have been inconclusive in terms of the actual results, negative or positive, from location to location.

Although overfishing and negligent fishing practices may not necessarily have a direct effect on the physical or chemical make up of the reef, impacts on fish populations with respect to human interest is often regarded as the main concern (Sadovy de Mitcheson et al., 2013). With reef-bearing countries relying heavily on fish as a source of income, it has proven to be difficult to completely eradicate mal-fishing practices (Gibson et al., 1998). Key issues include commercial abuse, exceeding catch or size limits of certain species, fishing in illegal or protected areas, fishing and harvesting in spawning grounds, and fishing with gear that may cause harm to by-catch or the reef such as gillnetting, trawling, or spear fishing (Williams et al., 2011). By-catch, which is the harvesting of a non-targeted species can be a major concern during gill-netting and trawling operations and often leads to the death of the fish. If not done in moderation, fishing can decimate a population of fish species. Economic reward often outweighs the risk of punishment.

All of the fishing practices mentioned here present a major problem in altering the populations of various fish species that each play an important role in their effect on food webs that maintain the balance of ecological dynamics in reef setting. Larger species such as grouper, snapper, and hogfish are often more solitary in behavior, so when a large majority is removed from a specific stretch of reef, numbers may be reduced for years to come due to a lack of spawning opportunities and an imbalance in the food chain. Overfishing carnivorous fish such as grouper and snapper species can deplete predator populations and in turn alter the circle of life, allowing species that were previously preyed upon to flourish instead (Fenner, 2014). Herbivorous fish are critical in promoting the ongoing success of corals by removing algae, and so are needed to help maintain the reef structure overall in supporting such a diverse array of marine life. The map exhibited in Figure 7 shows the various fishing pressure, threats, and severities documented by CZMAI within the Belize Barrier Reef.

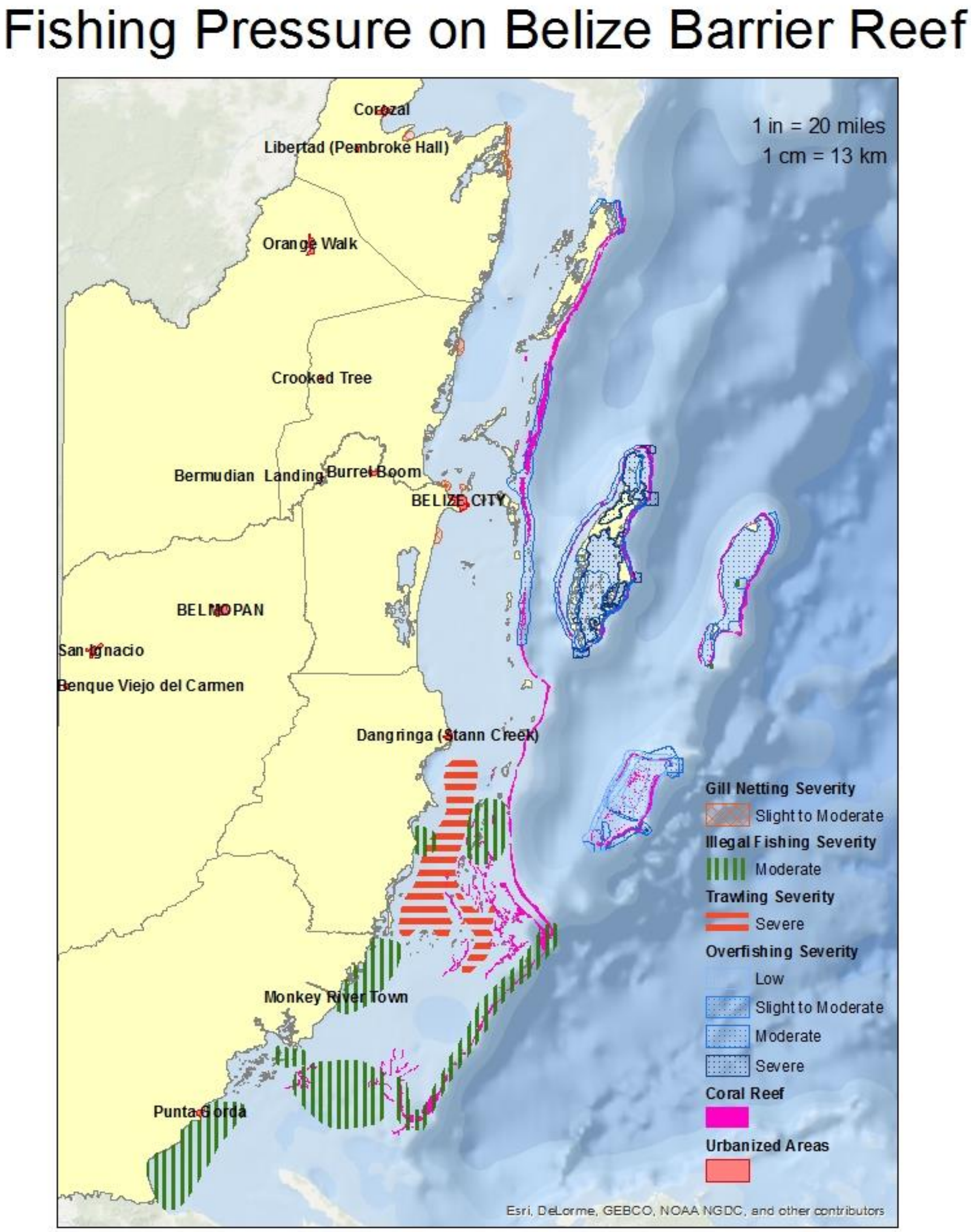

Figure 7: Fishing pressures on the Belize Barrier Reef (CZMAI)

1.4 Fish Species and Threat Vulnerability

The research in this thesis will focus on threatened and invasive fish species as reflected by relative abundance and sighting frequencies gathered in expert and novice dive reports from the REEF (Reef Environmental Education Foundation) citizen science database (REEF, 2012). The Belize Department of Fisheries and International Union for Conservation and Nature's "Red List" categorizes a series of fish species as critically endangered, endangered, vulnerable, or invasive (Belize Fisheries Department, 2011; IUCN, 2015). Several of the species on this list are the focus of this work. Of the seven species investigated here, Goliath Grouper are critically endangered, Nassau Grouper are endangered, Queen Triggerfish, Hogfish, Mutton Snapper, and Cubera Snapper are vulnerable, and the Red Lionfish is invasive (BFD, 2011). Each of these species carries unique traits that influence the overall well-being of the reef as a whole (REEF, 2014). Within the seven species, the only species that is not carnivorous is the Queen Triggerfish, which is a herbivorous grazer. Despite some legislative action, there is still an overwhelming need for stricter regulations on these species in the waters of Belize. When fluctuations in relative abundance and sighting frequencies are looked at over space and time, they can be useful for identifying patterns and potentially pinpointing specific environmental hazards affecting these fish and the reef in its entirety (Da Silva, 2005). Table 1 at the end of this section summarizes the risks posed to each species studied here.

1.4.1 Critically Endangered

The Belize Department of Fisheries deems the Goliath Grouper as *critically endangered*. The Goliath Grouper is susceptible to a number of factors that relate to a steadily decreasing population not only in Belize, but throughout the Atlantic. The Goliath Grouper is a slow growing and heavily sought after game fish due to its eventual size of up to several hundred pounds. Although substantially protected, the size and annual reproduction rate make rebound in a population difficult (IUCN, 2015). Furthermore, smaller juvenile Goliath Grouper tend to congregate in shallow mangroves as they grow and hide from predators (IUCN, 2015). The increase in coastal development in recent years has decreased the amount of shoreline mangroves, leaving juvenile Goliath Grouper more vulnerable in certain areas.

1.4.2 Endangered

Nassau Grouper are labeled *endangered* in the waters of Belize and the species has seen an estimated 60% decrease in populations worldwide over the last three generations (IUCN, 2015). Heavily targeted as a game fish and table fare, Nassau Grouper is steadily declining throughout the Mesoamerican Reef and Caribbean as a whole due to overfishing of the species as well as a loss of spawning aggregation sites (Patterson et al., 1999; ICRI, 2015). The species is heavily targeted during its annual spawning time and over harvesting of the species in a spawning site often leads to the population no longer being viable at such locations (Patterson el al., 1999). With spawning sites for Nassau Grouper decreasing rapidly, it is estimated that only two spawning aggregation sites remain. These two are now protected areas in Glovers Reef and Sandbore Caye (IUCN, 2015).

1.4.3 Vulnerable

Fish species of the Belize Barrier Reef listed as *vulnerable* by the Belize Department of Fisheries include the Queen Triggerfish, Hogfish, Mutton Snapper, and Cubera Snapper. To be classified as *vulnerable*, a general decline is seen in the population over several generations (REEF, 2014). Each of the listed species are noted as having a decreasing population, with the reason due to negligent commercial fishing practices and harvesting. However, it is also to be noted that juvenile Queen Triggerfish are often a prey item to the invasive Red Lionfish and are highly susceptible to changes in seagrass levels as they use the hard sandy bottom to build nests. Mutton and Cubera Snapper are heavily harvested during their annual spawning aggregations and are losing viable spawning sites in the Belize Barrier Reef at an increasing rate despite efforts to ban fishing for the species during the spawning period (Granados-Dieseldorff et al., 2013).

1.4.4 Invasive

The Red Lionfish is an invasive (non-native) species that is endemic to the Indo-Pacific region. This species was first documented in the Atlantic Ocean in Dania Beach, Florida in 1985 and has gradually worked its way into the Caribbean and across the Gulf of Mexico into Central America (Ruttenberg et al., 2012). In 2008, the Red Lionfish was spotted inhabiting a section of the northern most point of the Belize Barrier Reef (IUCN, 2015). Its impact has since spread the entire length of the Mesoamerican Reef System, and has increased in population and sighting frequency throughout the barrier reef adjacent to Belize. Like most invasive species, Lionfish encompass the ability to reproduce at a rapid rate, occupy many different marine settings, compete with and consume more prey than its competitors, does not have any real threats to its own livelihood, and is not recognized as a predator to many fish in the Western Atlantic (Albins et al., 2013). Lionfish may have a direct influence on the vulnerable status of the Queen Triggerfish due to juveniles serving as a prey item, as well as Goliath and Nassau Grouper, and Mutton and Cubera Snapper as they both occupy the same trophic zones and often compete for the same food source (Arias-Gonzalez et al., 2011; Rocha et al., 2015). Lionfish have been found to have 2.4 times the negative impact on reef fish populations compared to other predators and have been shown to consume 90% of the prey fish population over a two month period in comparison to only a 35% reduction to native Coney Grouper (Cox et al., 2013). This, accompanied by the venomous spines, ability for females to reproduce up to every four days for a potential of 2 million eggs per year make for a quickly increasing population throughout the barrier reef system (Albins et al., 2013). Lionfish also consume herbivorous prey which leads to a decrease in algae consumers and can create an imbalance in the growth of algae lowering the survival rate of corals.

1.4.5 Factors Affecting Individual Species

Table 1: Species vulnerabilities

Species	Classification	Vulnerabilities
Goliath Grouper	Critically Endangered	• Mangrove clearing results in habitat loss for juveniles • Overfishing • Low reproductive rate
Nassau Grouper	Endangered	• Overfishing • Spawning aggregation sites at risk • Habitat risk
Queen Triggerfish	Vulnerable	• Commercial fishing bycatch • Susceptible to sedimentation over seagrass nesting areas • Juveniles often preyed upon by Lionfish
Hogfish	Vulnerable	• Commercial fishing practices and harvesting • Seagrass bed depletion from sedimentation as juvenile nursery
Mutton Snapper	Vulnerable	• Overfishing • Spawning aggregation sites at risk • Seagrass depletion risk for juvenile habitat
Cubera Snapper	Vulnerable	• Overfishing • Spawning aggregation sites at risk • Loss of mangrove habitat impacts juvenile success rate
Red Lionfish	Invasive	• Little to no real threats other than cannibalism and human harvesting

1.5 Marine Protected Areas

Organizations such as the Belize Coastal Zone Management Authority and Institute (CZMAI), NGOs, and the government have pushed to create and enforce a system of marine protected areas throughout the entirety of the Belize Barrier Reef in order to protect the reef habitat and its inhabitants (Maidens & Burke, 2005). In 1998, 13 Marine Protected Areas and 11 Species Aggregation Sites spanning from Corozal Bay in the north, to Port Honduras and Sapodilla Cayes in the south were created with the goal to reduce the human impact and sustain a healthy population of several threatened species on the delicate barrier reef ecosystem (Maidens & Burker, 2005). A portion of this research looks into the effectiveness of the designation of MPAs to the Belize Barrier Reef by looking at the most threatened and invasive species abundance distributions both spatially and temporally. Understanding what sort of impact MPAs are having on certain species can foreshadow future planning of species sustainability on reefs. The MPAs, in Figure 8, are labeled as either “general use” or “no take” with additional legislative parameters set in place on the Species Aggregation Sites during key spawning occurrences in hopes to help certain species numbers rebound. Strict regulations on fishing and diving practices, as well as marine reserves and world heritage sites with additional regulations are implemented across each MPA throughout the year. However, through talking with locals, it was noted that the MPAs are difficult and expensive to patrol and enforce and are often abused.

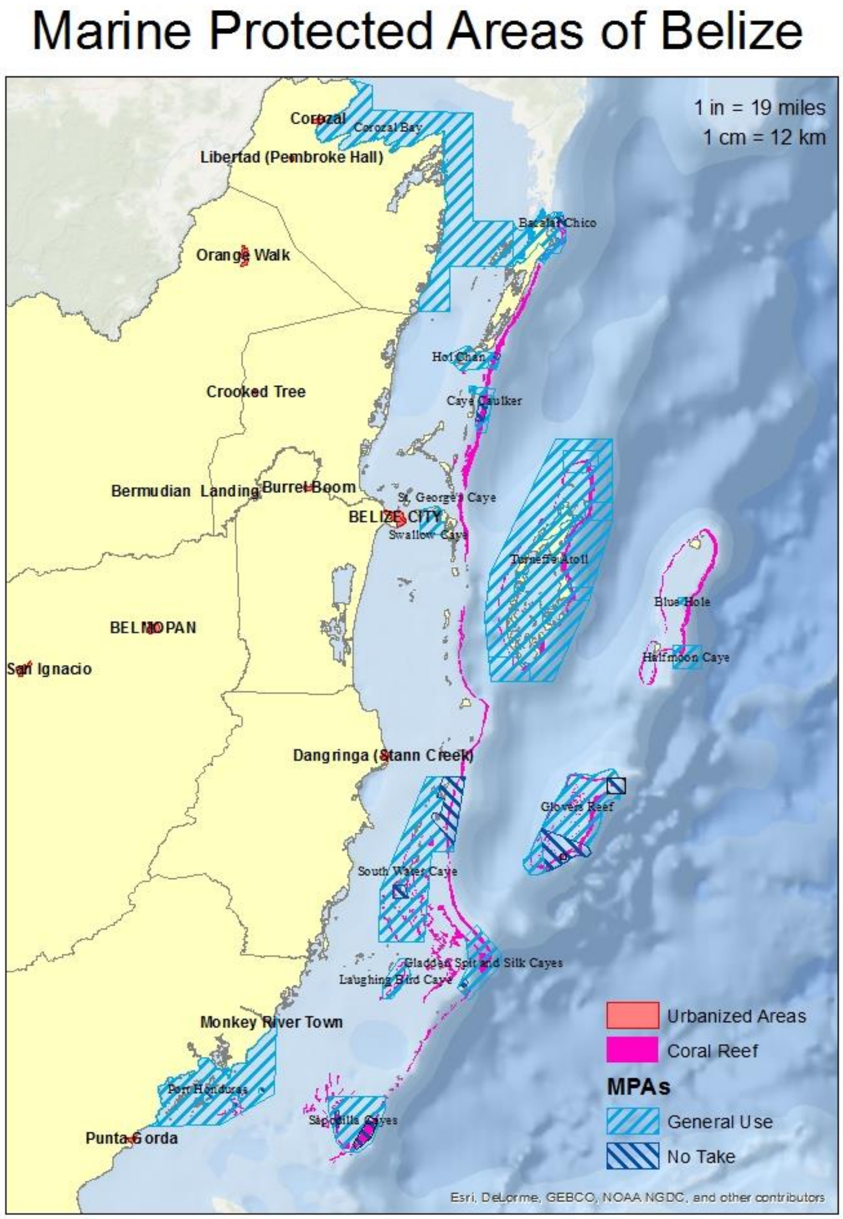

Figure 8: Marine protected areas of the Belize Barrier Reef (CZMAI)

1.6 GIS as a Tool for Understanding Reefs, Fish, and the Environment

The goal of this study is to use both fish and environmental threat data to understand the spatial and temporal relationship between these variables on the Belize Barrier Reef.

Incorporating two sets of data and mapping them together can help unlock the relationship between these entities and draw conclusions on the implications one source may having on another. Methods derived from similar reef settings can be useful in creating a methodological approach of how to best map the data in this particular study area. Many studies in the literature focus on either reef threats or fisheries data but few utilize an integrated approach of multiple entities being mapped comparatively. Works that do incorporate both fish and environmental data in GIS, but not specific to a coral reef setting include Pittman et al. (2011), Claisse et al. (2012), and Da Silva et al. (2015). Other literature on predictive management and sustainability spatial planning of species are relevant to this work in also analyzing multiple datasets in GIS. However, since the research done here is not aimed at creating future prediction results, examining the methods in how different datasets were integrated and interpreted proved useful (Douvere, 2008; Granados-Desieldorff et al., 2008; Walker et al., 2008; Guerry et al., 2012; Yates et al., 2013; Pittman et al., 2016).

Case studies focused on GIS-based methods in a marine setting were reviewed and several were used as models for analytical approaches for both REEF and CZMAI data as discussed further in the methods (Wright et al., 2007; Boden, 2010). Fish populations and abundances are commonly studied in GIS, but publications that utilize REEF datasets are rarely used in combination. Literature that focused on reef threats similar to those seen in the CZMAI data included Witold & Reytar (2012) and Arkema et al. (2014). One study of particular interest that did use REEF data in GIS and in conjunction with other spatial data examined benthic habitat associations with reef fish (Jeffrey, 2000). Other relevant studies to the objectives of this research related to investigating spatial distributions of species over time using abundance and frequency data in GIS for threatened and invasive biota (Holcombe et al., 2007, Longval, 2016).

Although no other studies were found to incorporate data on fish populations and environmental threats in GIS in the way that was done here, reviewing the literature was useful in developing several methodological approaches for this research.

2 METHODOLOGY

2.1 Field Work and Data Collection

Data for this research was compiled from multiple sources of spatial and citizen science-based datasets. Data sharing agreements were set up with the Reef Environmental Education Foundation (REEF) and Coastal Zone Management Authority and Institute (CZMAI). The data gathered from REEF included datasets on all species surveyed within the parameters of the reef including the focus critically endangered, endangered, vulnerable, and invasive species within the designated Zone 55 region of the REEF database for Belize. CZMAI provided spatial data containing datasets and GIS layers pertaining to environmental characteristics, fishing, designated areas of the Belize Barrier Reef, and land-based activities with the potential to reach the ocean.

Two trips to Belize were completed as a part of this research. The first was in May 2015 as part of a GIS-based study abroad course through the Department of Geosciences at Georgia State University. The second trip in November 2015 was exclusively for thesis research. These trips were used in order to meet with various organizations and locals to gather information on the reef and its inhabitants in the form of local knowledge, opinions, and data from individuals who work or live alongside the reef as well as to compare data from REEF surveys to personal findings. The ability to compare literature and datasets to the perspectives of locals or Belizean organizations offered an interesting comparison when trying to understand the status of the reef and certain fish species, and how environmental factors are impacting the barrier reef system.

In order to create a spatial analysis of fish and environmental factors affecting them, spatial data from CZMAI were first compiled and plotted in ArcGIS overlaying the "Oceans" basemap provided within the ArcMap platform. All of the spatial data was plotted in the geographic coordinate system "WGS 1984". A layer that included highly urbanized area was also added as a reference tool for the viewer. This high population density area was obtained from datasets made public by the Central American Commission on Environment and Development (CCAD). These recreated maps are shown in this work as Figures 1-8.

2.1.1 Data Sources

Spatial data from the Belize Coastal Threat Atlas created by CZMAI was obtained and employed as the primary spatial dataset for environmental data, bathymetry, coastal habitats, marine protected area boundaries, fishing pressures, and marine- and land-based threats. Spatial data that were obtained for this research came in the form of raw spatial data as GIS layers, shapefiles, and spreadsheets that needed to be transferred into an ArcGIS setting. The CZMAI data were added to ESRI's ArcMap GIS software, and parameters pertaining to the data, previously created analyses, and symbology could be altered or expanded upon from the original maps composed for the annual Belize Coastal Threat Atlas (2005).

The Reef Environmental Education Foundation (REEF) database acted as the primary source for data on the targeted species. The REEF Database is a citizen science survey effort that allows expert and novice information to be collected during dives after which it is submitted and stored in an online database available to the public. Using the REEF database as the main source of fish data in scientific studies is recognized and accepted as a credible and accurate source of fish data as evidence in part by many scientific publications and reports that can be viewed on the REEF publications section of their website (Wolfe et al., 2013; Thorson et al., 2014). A series of excel spreadsheets were obtained from REEF detailing every survey entered from 1994 until 2015 spanning the entire area of the Belize Barrier Reef within the designated region categorized as “Zone 55.” The dataset included dive logs, or surveys as they are referred to in this study. Within each dive log, each individual species sighting was given its own recorded entry and included abundance information, meaning each survey incorporated many different individual species sighting entries. There were a total of 3,349 surveys that included 145,623 individual species entries during the 22 year study period examined. Each survey was given a unique form ID, and contained information on the dive site and its corresponding coordinates, geographic zone code, date in which the dive took place, experience of surveyor, bottom time, average depth, bottom and surface temperature, visibility, current, habitat code, species codes of the fish species noted on the particular dive, family code, and abundance code for each noted species.

The REEF database designates four categories for abundance values entered into the survey database. The values for species abundance were entered as ranked bins such that 1 indicates a single sighting of a species (=single), 2 corresponds to 2-10 individuals sighted (=few), 3 reflects 11-100 individuals sighted (=many), and 4 represents over 100 sightings of a given species on a particular dive (=abundant). For more on the validity of the order of magnitude abundance bins that REEF uses as a reflection of fish populations, refer to Wolfe & Pattengill-Semmens (2013).

2.2 Data Preparation

Data from REEF were utilized in this research either in the form of annual sighting frequencies or as mean abundance values. Prior to GIS analyses, annual sighting frequencies of species were first determined without incorporating data from the abundance categories provided in REEF. The presence or absence of a species for each survey was noted, and then the proportional recurrence calculated upon considering all surveys in a year. For GIS analyses, abundance data were used instead to show spatial distributions over time for each species as well as acting as a general indication of the health of that species in a given location. Changes in abundance data including whether or not the species was reported were analyzed in GIS. In order to avoid overlapping data points when surveys were plotted, average abundances were determined and served as the primary source of abundance information to be mapped for these fish populations. This scoring method is utilized in a REEF monitoring study in the Florida Keys whereby average abundance was calculated by species, per year, per dive location (Jeffrey, 2004; Pattengill-Semmens, 2006). For example, if Nassau Grouper was reported in two surveys for the Hol Chan Marine reserve in 2001, one noting an abundance bin value of 1, and the other an abundance bin value of 2, a mean would be calculated and the resulting average abundance of 1.5 used for Nassau Grouper at that location in 2001.

The raw data from REEF had to be reformatted for use in ArcMap aside from calculating mean abundances. This step included converting coordinates into decimal form, joining locations due to multiple entries at the same locale, and cross referencing abundance and sighting frequency data for any anomalies. The REEF data were rid of all entries outside of those pertaining to the seven species used in this research. Each of the entries were then narrowed to include only survey ID, geographic zone code, site ID, survey date, species code, and abundance code. In order to conduct spatial and temporal analyses of the REEF data and have the dataset correctly join into ArcMap, the data had to be rearranged into two separate spreadsheet layouts in order to accommodate various types of tools and analyses.

The first spreadsheet was organized to look at species distribution over space and time and included survey ID, location, latitude, longitude, and a column corresponding to a single year for each of the targeted species. Each column contained the average abundance of a species for a given dive location in a given year. An example of this can be seen in Appendix B with abundance data from Nassau Grouper in the years from 1999 to 2004. The second spreadsheet layout was set up to look at abundance data by location for each year. Each of the 319 locales provided in the REEF dataset were listed for each year and stacked rather than strung side by side in the first spreadsheet. An example of this spreadsheet can be seen in Appendix C providing a more usable data format for completing analyses involving changes over time.

It should be noted that in order for the join of the spreadsheet to transfer correctly in ArcGIS, all null values were replaced with 0, average abundance calculated for each location per year in order to avoid overlapping of data points at a single location, and then the table imported into a geodatabase.

2.3 GIS Analysis

Using the spatial dataset seen in the Belize Coastal Threat Atlas produced by CZMAI (2005), and species abundance data provided by REEF, several analyses and data overlaying techniques were used to understand the spatial and temporal relationships between fish species, environmental factors and threats, and the implication of MPAs on the Belize Barrier Reef.

2.3.1 Mapped Threats to the Belize Barrier Reef

Each of the maps previously shown in relation to threats to the Belize Barrier Reef, its habitat types, and marine protected areas are based off of data gathered and made available through the 2005 Belize Coastal Threat Atlas by CZMAI (as reproduced here in Figures 1-8). Both threat severity and modeled threats were included. Modeled threat maps took into account several factors in order to produce predictive threat severity models that incorporate data on coastal development, marine-based threats, and agricultural runoff and sedimentation.

For the modeled threat of agricultural runoff and sedimentation, all of the runoff threats are directly variant on the discharge rates from a given watershed, meaning times of increased rainfall or runoff have an eventual direct influence on the discharge output into the reef and the data used were gathered from the latest dataset from CZMAI (Figure 3). According to the Belize Coastal Threat Atlas (2005), a 1-km buffer estimate was used to model the threat expanse based on land-type, slope, soil characteristics, and precipitation to determine erosion rates, which were then categorized by individual watershed to determine sediment delivery at the river mouths leading into the barrier reef. These end estimates were then modeled as plumes to show the breadth to which the sediment delivery can reach, as well as the portions of the reef it overlaps. Areas where the modeled plume was estimated to reach were then categorized by CZMAI as a low, medium, or high threat to the reef based on proximity.

The modeled threat of coastal development takes into account location of population, infrastructure, and tourism development (Figure 5). Threats to coral reefs were determined by distance to human coastal development, ports, airports, and tourism centers and modeled using data from CZMAI. Threats to the reef are classified as low, medium, and high levels of severity.

A marine-based threat model was also developed by CZMAI for the Belize Coastal Threat Atlas and used in this research (Figure 6). According to that report, the threat to coral reefs was based on the proximity to ports and shipping lanes, dive centers, and the volume of cruise ships along these channels to create a modeled buffer zone ranging from low to high threat levels to the reef.

2.3.2 Tools and Analyses

The REEF data were plotted by dive site from coordinates, and have each locale mapped by abundance of the designated species. Using both the REEF data and CZMAI data, five analyses were conducted in order to address the research objectives laid out for this study pertaining to variations in spatial distribution of fish species over time, as related to environmental threats to the reef, the effectiveness of MPAs, and the status of the Red Lionfish. The CZMAI layers were overlaid on REEF species data to get an idea of which individual threats are observed across the entirety of the barrier reef system and infer which areas might be impacted more so relative to others. The data were plotted using different symbologies exhibiting graduated abundance, showing abundance of several individual species at a single location given a correlated one year time frame.

2.3.2.1 Percentage of Sightings by Year

In order to first address changes in fish populations over time, data were plotted to examine variation in annual sighting frequency for the seven species analyzed in this study. The total number of surveys entered into the REEF database were compiled and divided by year and species. For each of the seven species, the total number of recorded surveys that included a given species was divided by the total number of surveys taken for each year to produce a standardized percentage. This approach made it possible to analyze fluctuations in species sighting frequencies over time prior to examining abundance patterns in space.

2.3.2.2 Time Series Analysis

In ESRI Training Matters, Boden (2010) described how location-based data points can be used to map time. A previous case study in *Arc Marine: GIS for a Blue Planet* mapped species abundance in relation to time and used a time series approach and related tables based on chosen attributes to map (Thompson et al., 2005). Species average abundance over time can be mapped using a time series analysis by breaking up all of the individual species abundances by locale and year. The second spreadsheet format was used in the organization for this dataset (Appendix C). The time series analysis was used to create an animated video of the year-by-year changes to analyze change in spatial distribution over time. A time interval of one year was used with the data points for each year being displayed non-cumulatively. Also, the time series was coded to not display any data points with a value of zero in order to highlight the only the locations with abundance data. Once completed, it is possible to overlay the CZMAI layers to the mapped REEF dataset to observe the natural or human-induced environmental impacts on certain portions of the reef to see if a potential correlation exists between these threats and reports of species as well as a rise or fall in their abundances over time.

2.3.2.3 IDW Analysis

The use of an interpolation method such as the IDW analysis was utilized to identify potential areas in which a given species tends to congregate and to look into what factors or threats are present or not present, and why certain areas have higher abundances compared to others. This could be referenced back to the opposite scenarios in which there are lower observed abundances (or a lack thereof) and aid in better understanding why that may be the case by looking into the difference in factors between the various locales. The total species data of a given year separated by dive locations on the reef is used as the input feature class with the average species abundance used as the input field. This analysis allows for the identification of areas with high and low abundances which could then be compared year to year to look for changes in high-density areas. For the analysis, average abundances were taken for each year at each dive location and input into the IDW analysis in ArcMap using the first spreadsheet format (Appendix B). An IDW analysis was run for each year for each of the seven species and the resulting maps were put into a slide transition format to be viewed sequentially. The analysis was run to the processing extent of the Belize borders and districts shapefile and incorporated the maximum extent of all of the survey locations. The analysis was shown with the graduated colors symbology in which white and red represented areas with higher concentrations of a given species and greens reflecting lower concentrations.

2.3.2.4 <u>Threat Score</u>

The threat score analysis was incorporated into this study as a way to look at the individual threat levels each survey location is undergoing in comparison to the modeled threat maps for sedimentation and agricultural runoff (Figure 3), coastal development (Figure 5), and marine-based (Figure 6) threats. In order to complete this analysis modeled threats were assigned a score based on the low, medium, or high threat severity level given in its respective map derived from the 2005 Belize Coastal Threat Atlas. In a non-weighted approach developed for this study, classifications relating threats to number were created. A number of 0 was assigned for no threat, 1 was assigned to a low threat level, 2 to moderate or medium threats, and 3 to high level threats. For each of the three modeled threats, each survey location was assigned one of the previously mentioned numbers 1-4 depending on where the location was in relation to the modeled threats. For instance, a location that lies within an area designated as a high marine-based threat level zone would be assigned a 3 next to their location in the spreadsheet under the marine-based threat column. If the location does not lie within any of the modeled threats it will be given a score of zero.

With each survey location receiving a score for each of the modeled threats, the maximum possible score that could be received would be a 9, while the lowest would be a zero if the location does not lie in any of the three modeled threat zones. Essentially, upon having a higher total threat score once all three modeled threat scores are tallied for each location, it would be hypothesized that those areas would be more challenging for fish species to thrive and would thereby show fewer reports and lower abundance scores of at risk species. Conversely, a total threat score of zero would be hypothesized to be a prime location for fish species to thrive without the risk of hazards or threats and would therefore be expected to show more reports and greater abundances of those species at such locations in the REEF database.

Each total threat score was then plotted in GIS based on their coordinates and shown in the map using the gradual color symbology. The symbology was composed of five levels with red being the highest hypothesized threat level and green being the lowest. The goal with this analysis is to provide a level classification for each location and look at which areas on the reef were most at risk.

2.3.2.5 MPA Effectiveness

Wright et al. (2007) provides a key case study incorporating the effectiveness of MPAs using the spatial query method to analyze points that lie within the designated areas. This method was replicated in this research using the data obtained from REEF and CZMAI. An analysis based on species abundance throughout the reef as well as inside the newly created MPAs before

1998 and after proved be beneficial to understanding the success rating of the MPAs and observe whether they had the positive impact on protecting fish species like they were intended to have. A spatial query was used to focus on data specifically in the MPA polygon zones provided in the CZMAI dataset and compared it with species reports from REEF before (1994-1998) and after (1999-2004) the introduction of MPAs in 1998. Since REEF data only became available in 1994, the five year interval was replicated following the year of the MPAs inception in 1998, so 1999-2004, in order to see the relative results. The exception to this is the Red Lionfish, which was not noted in REEF surveys until 2007 and is analyzed from 1994-1998 and from 1999-2015 for assessing the invasion overall. Further analysis with 1999-2015 data can be also compared for other species and may show the long-term impact the MPAs have on the reef fish species sustainability, but it may be skewed due to other factors that might be at play over a longer time interval.

3 RESULTS

In conjunction with the research objectives set for this study, analyses used here were aimed to understand how fish data can be modeled across space and time. Incorporating approaches such as the percentage of sightings by year, time series, and IDW can be used to interpret species distribution trends over time, and in relation to several modeled threats to the reef. The threats not only include aspects of the changing environment, but also incorporate the negative impact that invasive species can cause in disrupting the reef ecosystem. A major part of understanding the spatial and temporal relationship between fish species and changes to the environment is also looking for sustainability options aimed to maintain a healthy habitat for the unique biodiversity encompassed within a barrier reef system. MPA effectiveness can address that objective by translating species abundance data both before and after the inception of protective boundaries on the reef. Results drawn from these analyses can lead to a better understanding of the relationship between fish across space and time and draw connections to the natural and anthropogenic impacts that alter distributions of certain species in Belize.

3.1 REEF Database Survey Extent

The extent of the study area and REEF survey locations used in this work can be seen in Figure 9. The survey locations span the stretch of the barrier reef including the outer reefs and atolls and act as the parameters to which all results were interpreted.

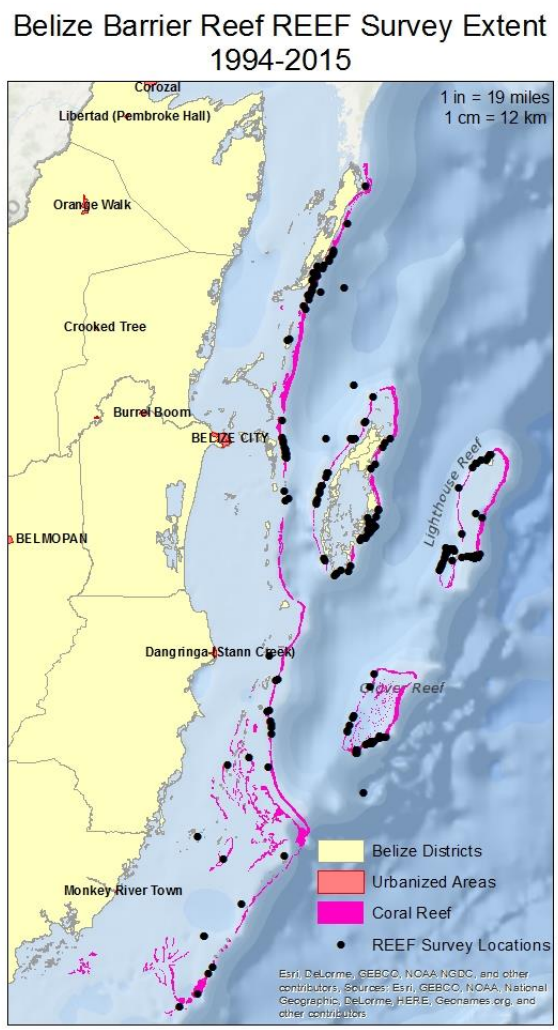

Figure 9: Study area and extent of REEF database surveys

3.2 Percentage of Sightings by Year

Calculating the percentage of surveys that included a given species in relation to the total number of recorded surveys for each year can be used as a proxy for examining variation in fish populations over time. The surveys contained 145,623 individual species sighting entries that were logged from 3,349 individual surveys. Of the 145,623 individual species sightings, 4,980 were from the seven target species making up 3.42% of the total species entries. Individual species were well represented in surveys overall with the exception of Goliath Grouper and Cubera Snapper (Table 2).

Table 2: Percent of surveys with target species recorded

Species	Number of Surveys Sighted	Percent of Surveys with Species
Goliath Grouper	17	0.51%
Nassau Grouper	1427	42.61%
Queen Triggerfish	1046	31.23%
Hogfish	1380	41.21%
Mutton Snapper	559	16.69%
Cubera Snapper	172	5.14%
Red Lionfish	379	11.32%
Total Surveys	3349	

The frequency of sightings for Goliath Grouper declined and then fell to zero in 2006 (Figure 10). There was limited data on the species, yet the percentage of surveys incorporating Goliath Grouper data in relation to the total number of surveys conducted per year confirm the status that this species is extremely rare and critically endangered on the Belize Barrier Reef.

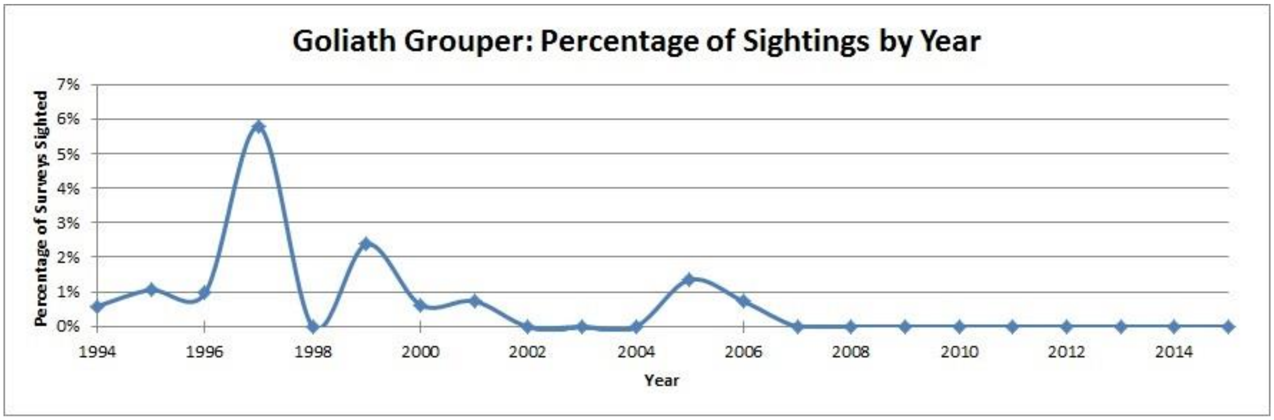

Figure 10: Goliath Grouper percentage of sightings by year

The number of Hogfish entries in relation to all surveys submitted annually resulted in a slow but steady decline from 1994 to 2015 with a few high and low anomalies from 2002 to 2005 (Figure 11). In general, the percentage of surveys that included Hogfish fluctuated around and fell from roughly 50-60% to 20-30% of all surveys over the time period analyzed. This indicates a steady and gradual decline in Hogfish abundance populations across the time span.

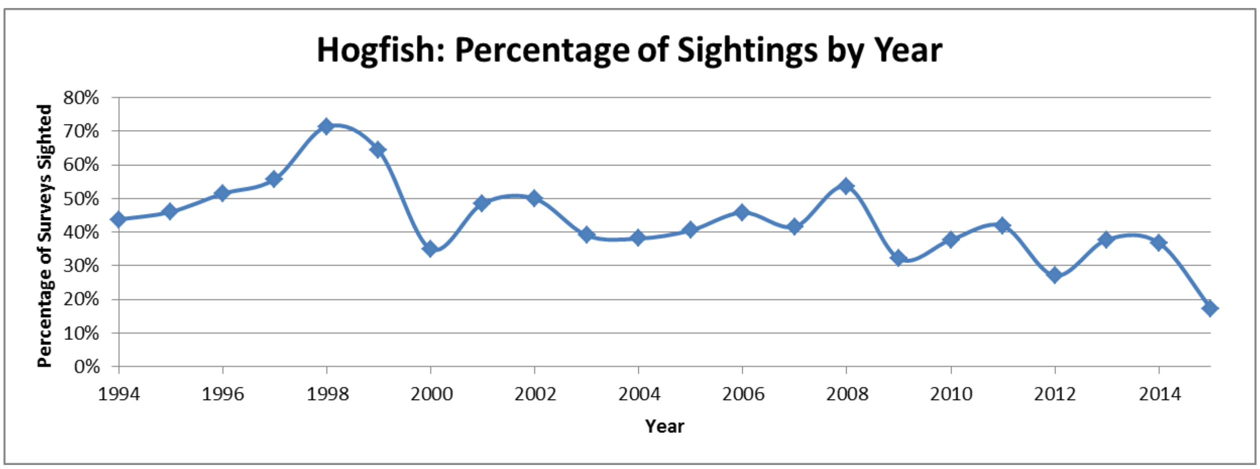

Figure 11: Hogfish percentage of sightings by year

Queen Triggerfish results (Figure 12) revealed a gradual decline in survey percentage from 1994 to 2005, with 2005 being the lowest recorded survey percentage at 11% of all survey entries. However, from 2005 to 2015 the results indicated a noticeable increase of Queen Triggerfish seen with the average percentage being 30% of all surveys. From a general overview, it appears that there is a decline from 1994 to 2003, from 2004 to 2007 a shift occurs from a gradual decline to a slight increase with 2005 being the low point, and then from 2007 to 2015 frequency of sightings continues to rise.

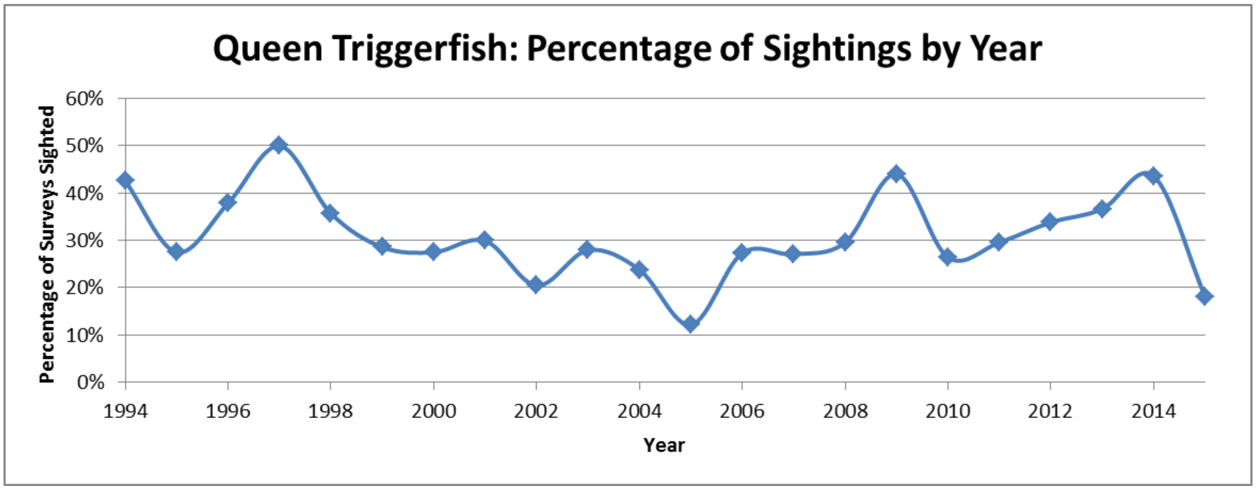

Figure 12: Queen Triggerfish percentage of sightings by year

Results of the number of Mutton Snapper entries in surveys indicate a steady increase in population (Figure 13). The percentages appear steady from 1994 to 2002 and begin an upward trend in sighting frequency within the total surveys from 2003 onward. There is some fluctuation in numbers from 1999 to 2003; however, from 2004 on a noticeable increase is observed.

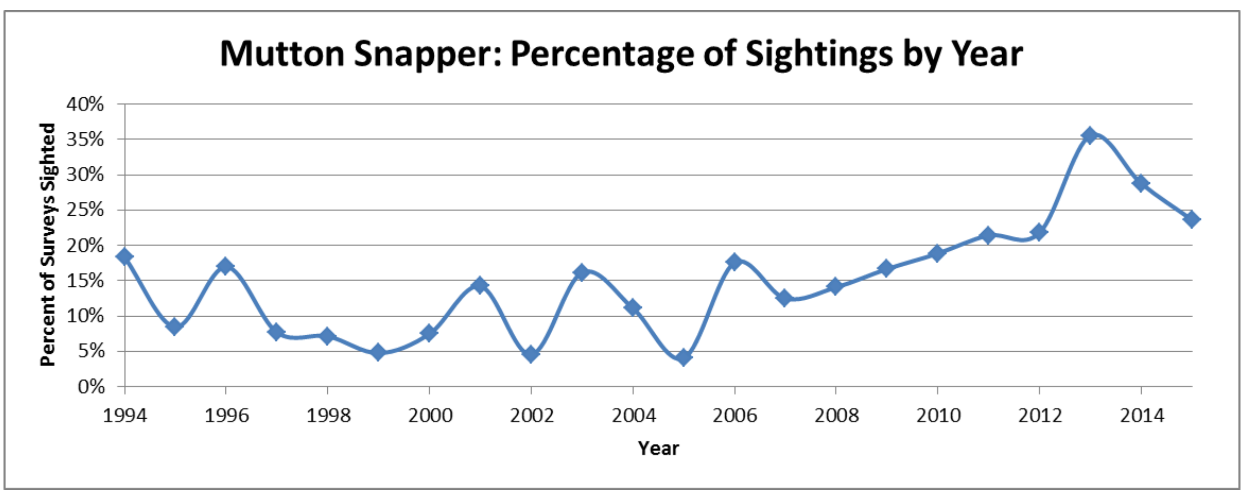

Figure 13: Mutton Snapper percentage of sightings by year

Both the Nassau Grouper (Figure 14) and Cubera Snapper (Figure 15) have a similar result over time. Both species experience a relatively consistent trend from 1994 to 2012 and then they tail off downward towards the end for more recent years. Cubera Snapper on the other hand experienced a small but gradual increase in survey percentage from 1994 to 2012 followed by a major drop from 2013 to 2015. The rapid decline seen in the final three years of surveys in both species results may indicate a decrease in species abundance.

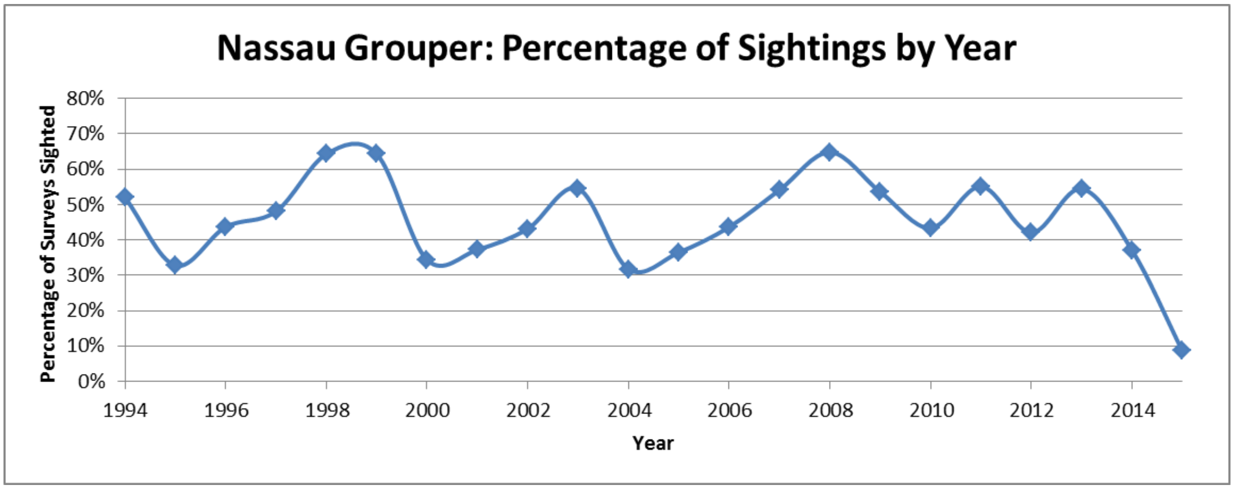

Figure 14: Nassau Grouper percentage of sightings by year

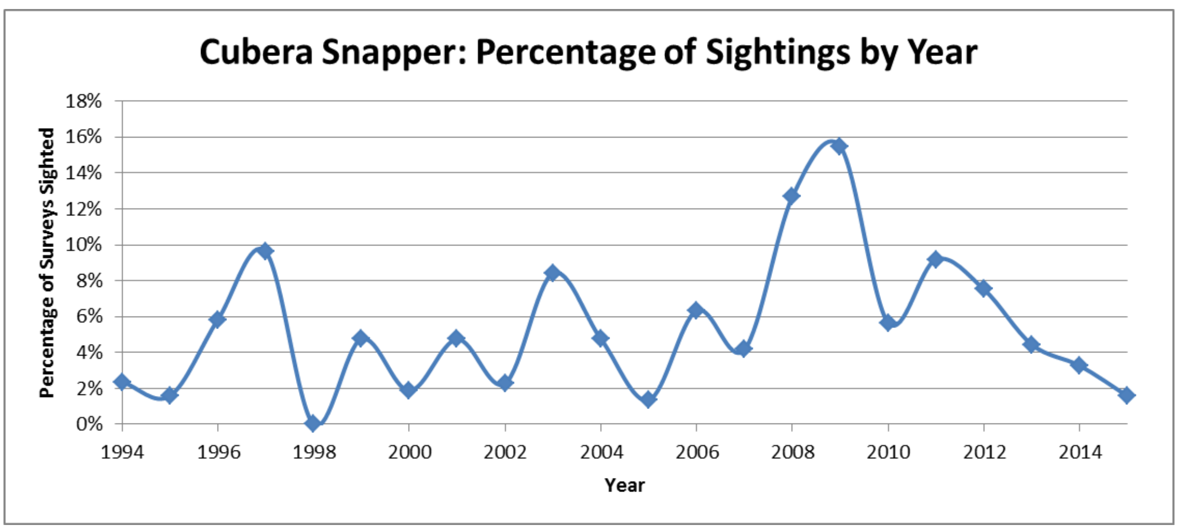

Figure 15: Cubera Snapper percentage of sightings by year

The invasive Red Lionfish survey percentages resulted in a rapid increase in the overall sighting frequency (Figure 16). From 1994 to 2006 there was no survey data on the species resulting in a steady flat line of no sightings reported. 2007 marks the first year that included survey data for the Red Lionfish and from 2007 to 2015 there was a substantial increase in the species sighting frequency from 0% reported to as many as 56% of all surveys documenting this invasive species.

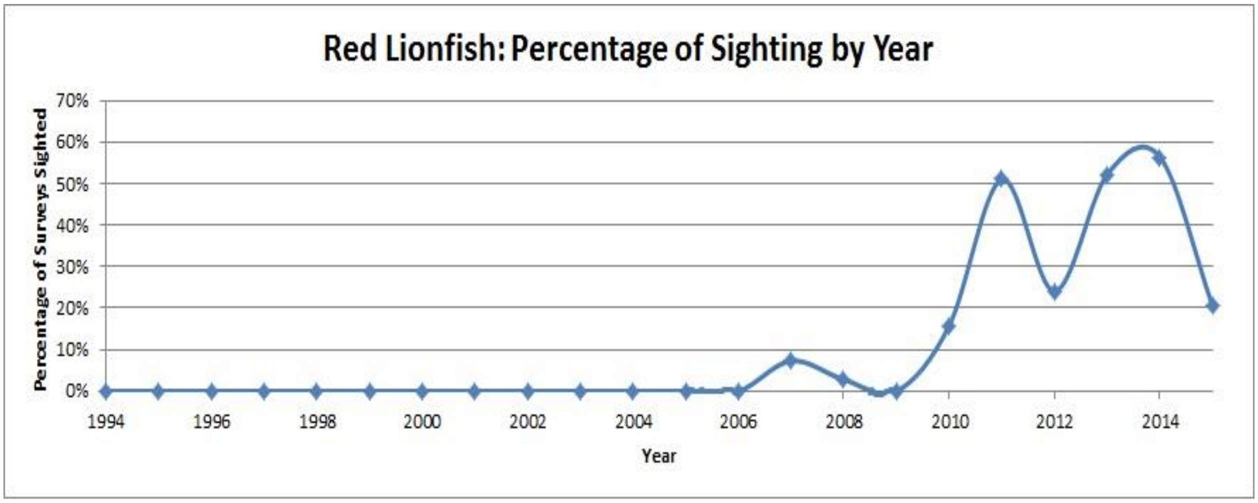

Figure 16: Red Lionfish percentage of sightings by year

3.3 Time Series Analysis

The time series analyzed individual location species abundances that could be compared to environmental factors as well as general spatial distributions across the reef. In order to view the time series analyses for each species, follow this link (http://citizensciencegis.org/belizefish). Noticeable species distributions and relationships to threats were analyzed within each analysis (Table 3).

The time series analysis revealed no discernable species distribution patterns across the reef for Goliath Grouper and Nassau Grouper. The Goliath Grouper offered limited data while the Nassau Grouper abundance data was scattered throughout the reef in no particular pattern.

Queen Triggerfish results indicate an abundance of species data in the atolls and outer reefs as well as throughout the northern portions of the reef with very few observed in the southern portion of the barrier reef system. Hogfish abundance data did not yield a discernable distribution trend across the reef in any particular area in the early years but did indicate the species abundances were slightly more condensed in the northern section of the reef towards the end of the time span analyzed. The Mutton Snapper results show that across 1994 to 2015 in early years the species congregates mostly in the outer atolls and southern portions of the reef. However, later years indicate that concentrations of the species are moving inward from the atolls and outer reefs as well as towards the north. The Cubera Snapper analysis resulted in the distributions across the central atolls and in the northern regions of the reef.

When the results were overlaid with the CZMAI modeled threats, several relationships to species distributions were noticed. Queen Triggerfish and Mutton Snapper were rarely correlated with areas associated with marine-based threats. Cubera Snapper were not mapped in areas of modeled coastal development or marine-based threats. Nassau Grouper were the only species to show up in areas of the reef under the high threat severity categorization. There was no relationship observed between Hogfish and the modeled threats.

Red Lionfish indicated a rapid increase and spread across the region after the first year it was documented in Belize in 2007. The species abundance trend starts in Lighthouse Reef and Turneffe Atoll and moves steadily from the north to south of the reef and has yet to reach below Dangriga in the Stann Creek District. Environmental factors do not appear to play a role in the movement of this species.

Table 3: Time series analysis findings

Species	Spatial Distribution Pattern	Relationship to Threats
Goliath Grouper	• No discernible pattern	• No discernable pattern
Nassau Grouper	• No discernible pattern	• Appeared in areas of high threat severity
Queen Triggerfish	• Outer atolls and reefs • Northern portion of reef	• Not found near marine-based threats
Hogfish	• Noticeable concentration towards end in northern portion of reef	• No discernable trend
Mutton Snapper	• Early distributions in outer atolls, reefs, and in south • Later years resulted in a push in from atolls and North	• Not found near marine-based threats
Cubera Snapper	• Central atolls, mainly Turneffe Atoll • Northern portion or reef	• Not found near coastal development or marine-based threats
Red Lionfish	• Spread rapidly in north and outer atolls following 2007	• Appear in areas of all modeled threats

3.4 IDW Analysis

The IDW or inverse distance weighted analysis was similar to the time series findings except it examined density concentrations of average abundances rather than individual locations. The outcome projects areas of concentration as areas of higher density in white and red, with lower concentrations in green. These areas of higher sighting frequency tend to appear as concentric circles of white and red. IDW analysis results will be posted on the following link in order to view the change over time (http://citizensciencegis.org/belizefish).

The Mutton Snapper results showed that from roughly 1994 to 2012 there was a consistent trend of higher concentrations on species abundances in the outer atolls of Turneffe and Lighthouse specifically along with areas of higher density in the central and southern portion of the reef. There were however a few anomalies or outliers in the data such as the years of 1998 and 2007 where no concentrations were shown, as well as 2003, 2005, and 2006 where higher concentrations were produced in the north near Ambergris Caye. 2008 marked the last year where the results noted higher concentrations in the southern portion of the reef below Glover's Reef. From 2008 to 2015 the trend seemed to be generally consistent with higher concentration areas being located in the central portion of the reef around Turneffe Atoll as well as higher densities in the north near Ambergris Caye that had not been previously found with any sequential year consistency.

Both Hogfish and Nassau Grouper results yielded robust data but no apparent pattern in distribution. However, Nassau Grouper indicated consistent high-density areas around the Lighthouse and Turneffe atolls across the 22-year time span, but no consistent trends were observed for the northern or southern portions of the reef despite showing up in both regions intermittently over the years. Hogfish resulted in high-density areas at various sites within the

Turneffe Atoll across all years with the exception of 1998. Aside from abundance of data and consistent concentrations within Turneffe Atoll, remaining results showed an inconsistent pattern of abundance across the reef ranging from the furthest dive locale in both the south and north.

Queen Triggerfish results yielded no discernable pattern across consecutive years. However, it was noted that there was consistently a high-density area within the Lighthouse Reef in all years except for 1998 when there was an overall lack of data. When higher concentrations were observed, they were generally more prevalent in the south, with only a few small areas showing up in the northern section of the reef, but neither showed any real consistency in consecutive years.

The results for the Goliath Grouper were inconsistent due to an overall lack of data. The only areas of high concentrations showed up in 1997 in the southern portion of the reef near Placencia, and 1999, 2000, and 2006 in the north near Ambergris Caye in relatively small concentrations, but this is due to these years having very few Goliath Grouper surveys and no other areas for analyzing in comparison. From 2007 to 2015 there were no noted sightings of Goliath Grouper in the REEF Database.

The invasive Red Lionfish results showed a rapid increase of the species into region. From 1994 to 2006 there is no recorded data of sightings with the species, 2007 marked the first REEF survey data. A concentration first appeared on the Lighthouse Reef Atoll and spread inward towards Turneffe Atoll and portions of Ambergris Caye similar to the results demonstrated in the time series analysis. From 2007-2015 species concentrations steadily increased in range, trending primarily in the north and moving south. The furthest south it appeared was near Tobacco Caye with a small concentration also appearing on Glover’s Reef.

3.5 Threat Score

Threat scores were mapped with graduated colors with green being the lowest and red being the highest and most at risk (Figure 17). When mapped, the more threatened areas were located on the main barrier reef in closer proximity to the mainland, with parts of the reef immediately adjacent to Belize City deemed the most severely threatened areas. Survey locations on the outer atolls and reefs such as Turneffe, Lighthouse, and Glover all had lower threat scores. Areas with higher threat scores generally had lower species abundances than areas of lower threat scores.

Belize: Modeled Threat Severity to REEF Survey Locations

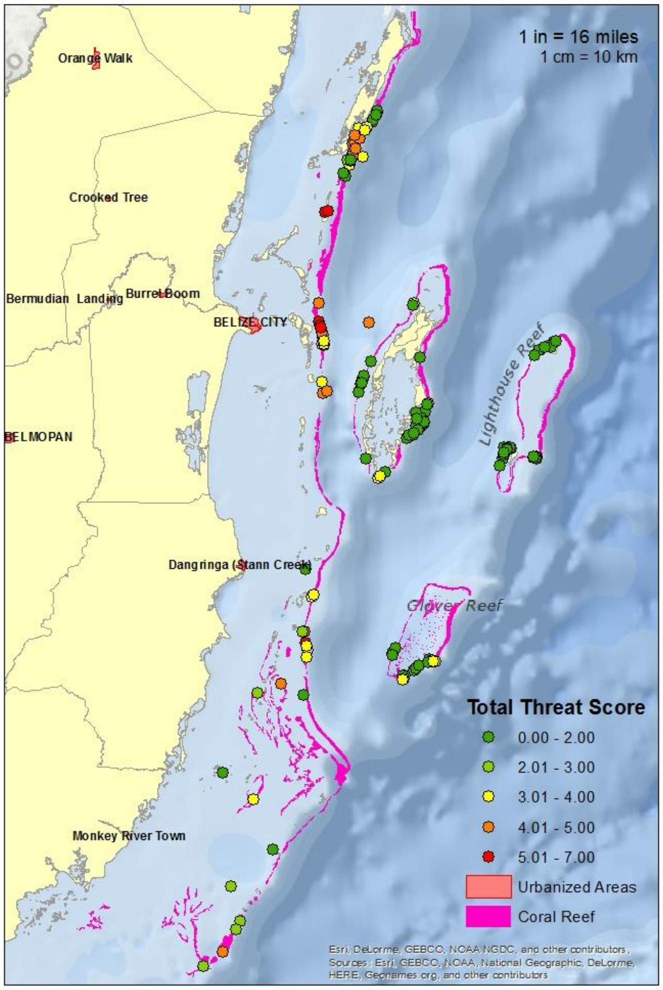

Figure 17: Threat Score Analysis

3.6 MPA Effectiveness

The Nassau Grouper (Figure 18) and Hogfish (Figure 20) analysis resulted in similar trends in which a general increase in reports and abundances was noted within the Turneffe Atoll MPA, and more significantly in the no-take zone in the southern portion of Glover's Reef. Mutton Snapper also showed a slight increase in areas such as Glover's Reef but not to the extent of the Nassau Grouper and Hogfish.

Fewer Queen Triggerfish were spotted in areas designated as MPAs (Figure 19). Turneffe Atoll, Tobacco Caye, and Sapodilla Caye all yielded lower observations of this species following the introduction of MPAs in 1998. However, the no-take zone in the southern portion of Glover's Reef resulted in a significant increase noted in the surveys of the REEF database from 1999 to 2003. A small portion of the reef in the Hol Chan Marine Reserve in Ambergris Caye also revealed a small increase in abundance following the introduction of MPAs.

Goliath Grouper, Mutton Snapper, and Cubera Snapper results were inconclusive. Goliath Grouper results were problematic due to a lack of data. Both Cubera and Mutton Snapper appeared to have relatively consistent results when comparing the data both before and after 1998. The only exceptions being an increase for the Cubera Snapper in the Hol Chan Marine Reserve off Ambergris Caye, and an increase in the no-take zone of Glover's Reef for the Mutton Snapper.

The Red Lionfish results were interpreted differently due to it being an invasive species that was not surveyed until 2007 (Figure 21). From 1994 to 1998 there were no sightings and therefore no abundance data to be seen on the map. However from 1999 to 2015, many individuals are spotted in Turneffe Atoll, with several other reports noted in Ambergris Caye, Lighthouse Reef, Glover's Reef, and Tobacco Caye adjacent to Dangriga.

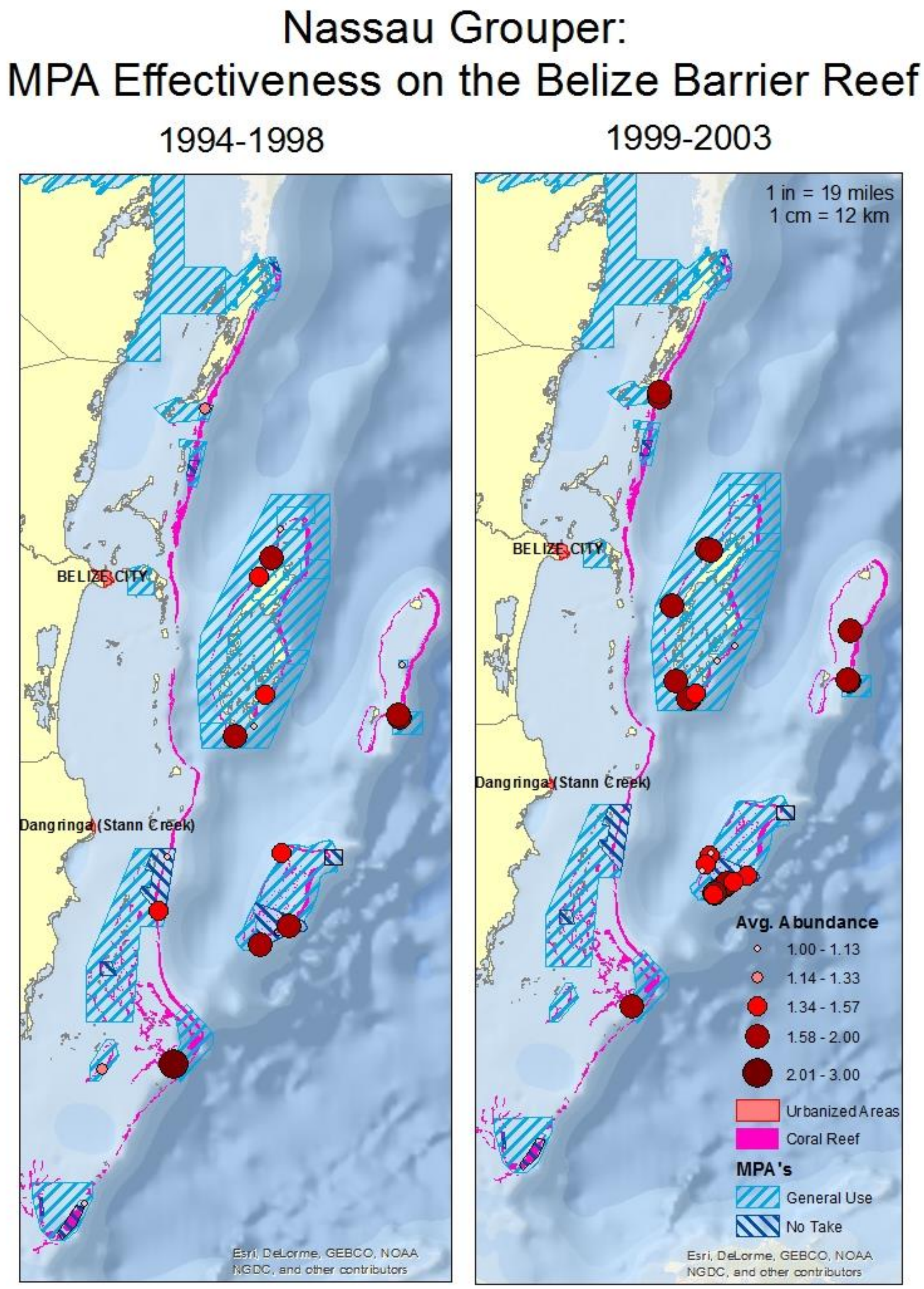

Figure 18: Nassau Grouper MPA Effectiveness

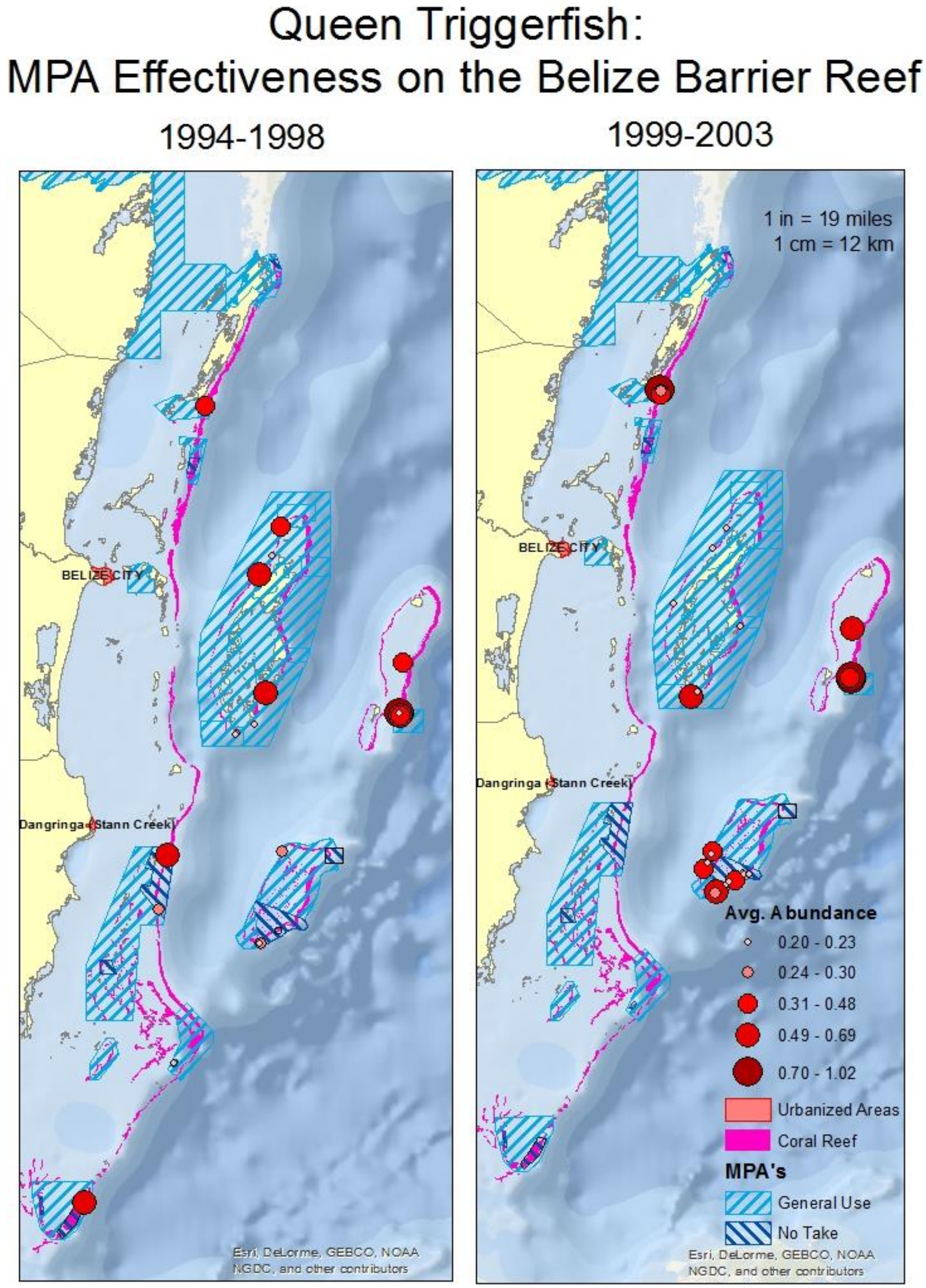

Figure 19: Queen Triggerfish MPA Effectiveness

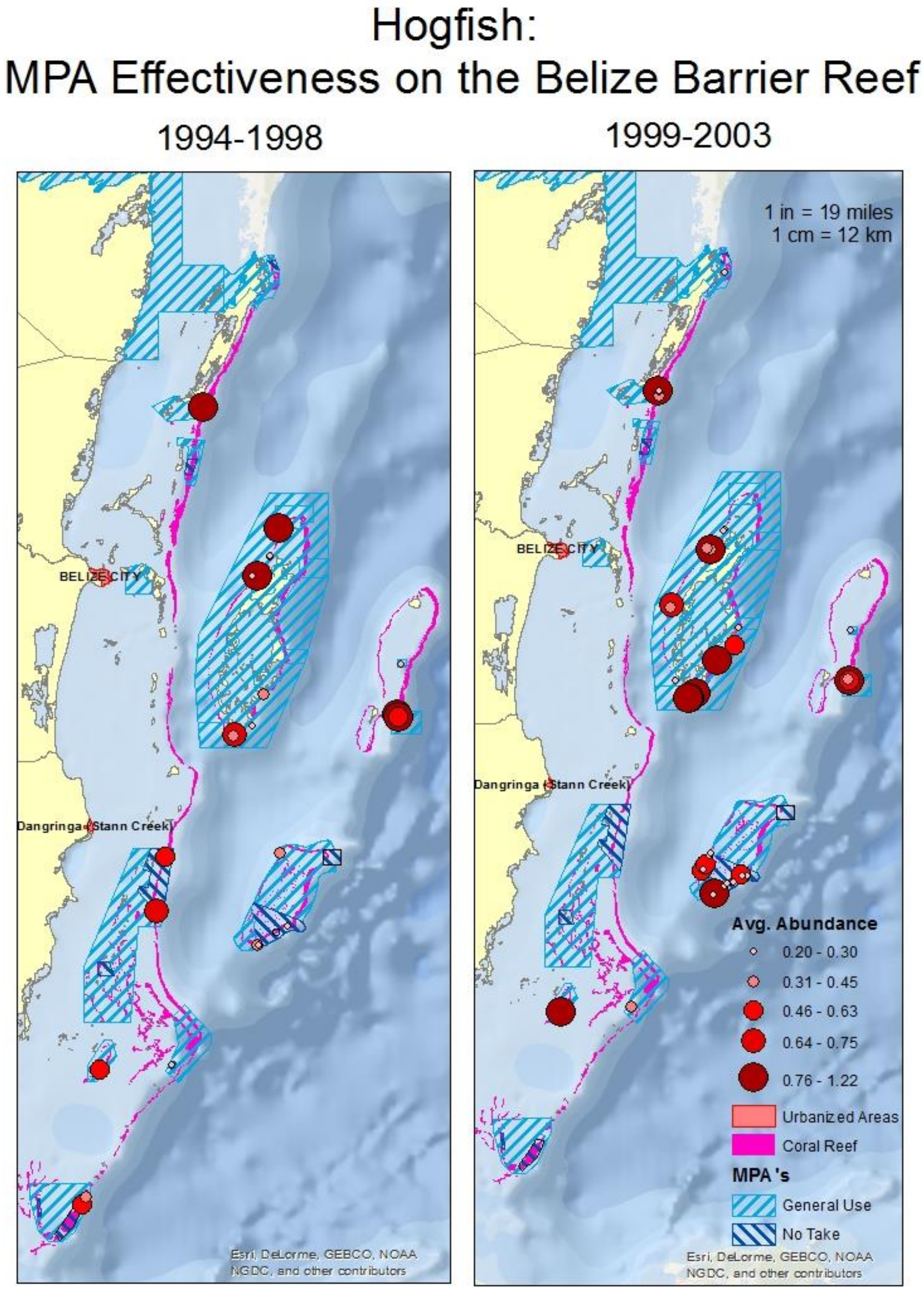

Figure 20: Hogfish MPA Effectiveness

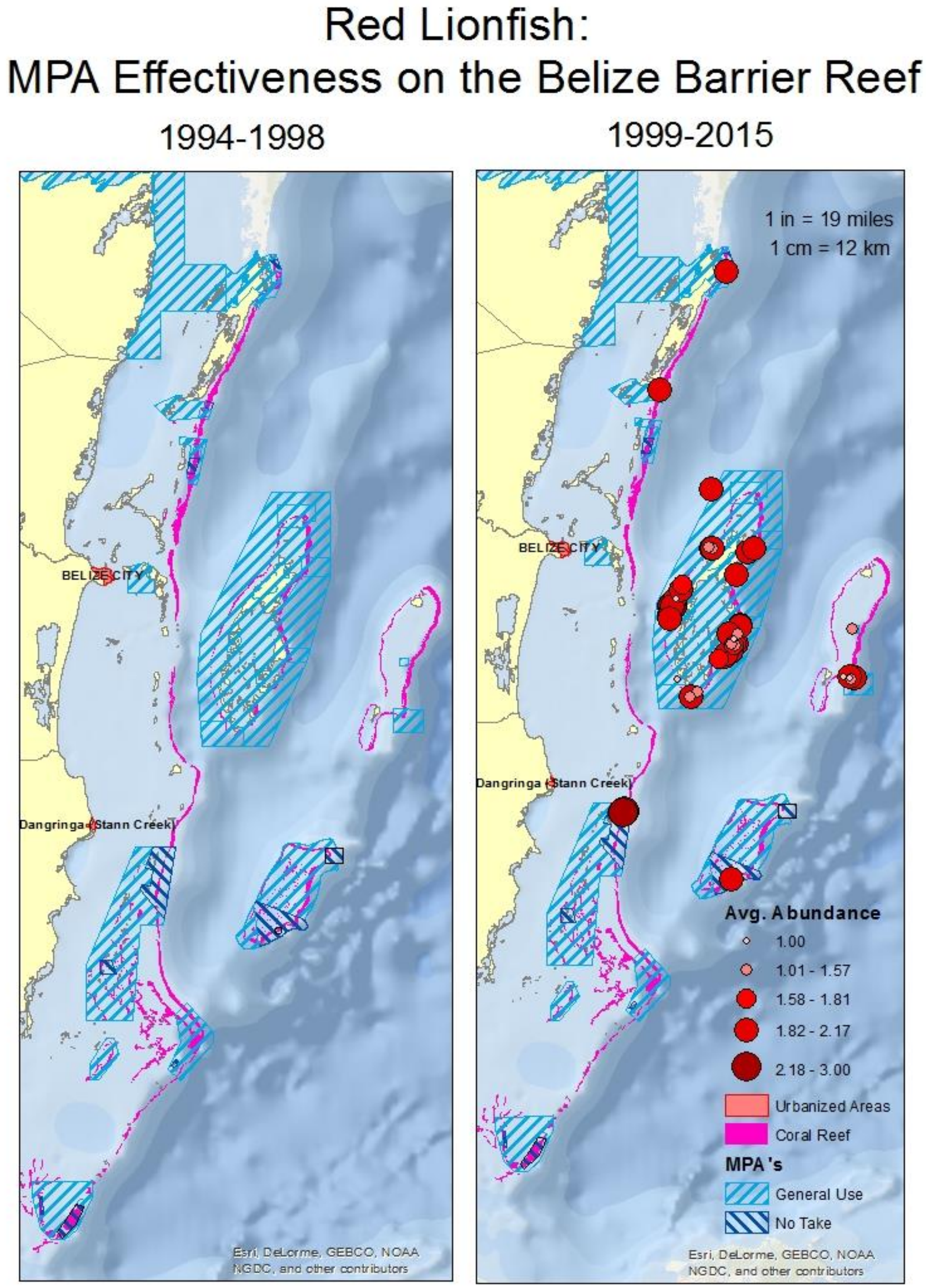

Figure 21: Red Lionfish MPA Effectiveness

4 DISCUSSION

4.1 Findings and Species Results Explained

4.1.1 Goliath Grouper

Goliath Grouper are classified as the most critically endangered species of the group of fish examined in this study. This created a challenge in gathering, displaying, and interpreting REEF data for the species. The REEF data gathered on the Goliath Grouper was so limited that it was difficult to make any conclusive results. With three surveys at most documenting the species in a given year and as low as zero in relation to up to hundreds of surveys entered yearly, interpreting the data and attempting to formulate trends was often too inconsistent to be deemed as a conclusive finding. The species was only seen in 0.51% of all of the total surveys (Table 2). Of the analyses, IDW, time series, and MPA effectiveness were all labeled as inconclusive or no pattern found. However, percentage of sightings by year has the potential to be interpreted as an indication of a decline in species population, but it must also be noted that it could be inconclusive due to the limited number of surveys with the species which will be discussed further in the limitations subsection. The frequency of sightings by year indicated a drop in species sightings from 1994 to 2015 with the tail end from 2006 to 2015 resulting in survey percentages of zero. This could indicate that that species is on the verge of being completely wiped out from the Belize Barrier Reef and also confirm its classification of being critically endangered. Increased mangrove clearing may have a detrimental impact on the juvenile Goliath Grouper as it will limit the habitat in which the slow growing species can inhabit (IUCN, 2015). With the low reproductive rates for the species in conjunction with it being a highly prized sport fish despite being protected by many laws and regulations, the future for the species in Belize looks grim.

4.1.2 Nassau Grouper

This species tended to exemplify a consistent scattered but stable in numbers trend in the IDW and time series analyses. In addition, it comprised the most survey data of any of the species targeted in this study showing up in 42.61% of all surveys (Table 2). This could indicate that the species is still being found throughout the reef and has the best potential for a rebound in its population. Analyzing MPA effectiveness demonstrated a small increase in the no take zones, of which the most successful was in the southern portion of Glover's Reef, one of the two remaining recognized spawning aggregation sites for the species. Otherwise average abundances tended to remain consistent elsewhere. Nassau Grouper can also be noted for being surveyed in areas deemed a high threat by the threat score analyses.

4.1.3 Queen Triggerfish

Trends and conclusions from the results of the Queen Triggerfish yielded mixed results in both spatial distribution and relationships to MPA effectiveness. The species appeared more often on the outer atolls and reefs such as Lighthouse Reef and less commonly in the south. An interesting point came up in the MPA effectiveness analysis, in that the species showed up more in some MPAs relative to others. One reason why this species in particular may have had a difference in these results may be due to its ecological characteristics as an herbivorous fish instead with a niche unique compared to the other fish studied here. Queen Triggerfish is generally considered less of a sport fish relative to other fish such as snapper and grouper. In April 2009, a national law was put into legislation for the ban of reef grazers harvesting. However, when reviewing the publications on this ban, legislation is aimed at the protection of parrotfish and surgeonfish with no mention of the Queen Triggerfish (Mumby, 2006; Fifth National Report to the United Nations Convention on Biological Diversity: Belize, 2014; ICRI, 2015). The Red Lionfish also acts as a threat to the species as juveniles serve as a popular prey item for the invasive predator. These factors may be more important than having MPA regulations protect them from overfishing or preserving diminishing spawning aggregation sites. This might make sense in why both increases and decreases in abundance in certain areas were noted, in that the species may not be benefitting as much from MPAs overall as other factors might be influencing their survival and susceptibility to habitat changes locally.

4.1.4 Hogfish

The Hogfish data analysis results may point to an interesting occurrence in the overall health of the population throughout the Belize Barrier Reef. It was found that the Hogfish IDW and time series data indicated that the species tends to congregate throughout the north, south, and outer reefs of Belize without necessarily indicating a pattern in high aggregation areas. The percentage of sightings per year indicated a downward trend in the sighting frequency across the 22-year time span. However, the MPA effectiveness analysis shows an increase in average abundance in the marine protected areas. This is interesting because it may indicate the effectiveness MPAs are having on the species in comparison to other locales outside the MPAs in which Hogfish were surveyed. With Hogfish abundances increasing within the MPAs and decreasing as a whole, this suggests that Hogfish within these designated areas are experiencing a much greater success that may be due more to the stricter regulations on fishing and perhaps fewer impacts of harmful threats being introduced to seagrass nurseries that juveniles inhabit, which may be encountered elsewhere.

4.1.5 Mutton Snapper

Mutton Snapper analyses resulted in several notable trends in the species' distribution both spatially and temporally. The results of the time series and IDW analyses showed a congregation of the species in the outer atolls and reefs with a recent slight movement of these reports inward. The species itself is vulnerable to several different changes to its habitat such as loss of seagrass and spawning aggregation sites and the results here could potentially be due to the outermost marine-based threats stretching into the outer atolls and reefs causing a shift in species movement inward away from newer threats in the edges of these reefs. It was interesting to note that Mutton Snapper seem to be increasing based on the species frequency of sightings by year results. Although the MPA effectiveness analysis did not yield a conclusive pattern, MPAs may still play a vital role in the potential rebound of the species. With snapper and grouper species in particular being popular sport fish, regulations posed in MPAs limiting fishing and usage practices may have a positive impact not only on the reproductive side of the species by adding more restrictions to known spawning aggregation sites, but by also by limiting the species as bycatch to fishermen.

4.1.6 Cubera Snapper

No noticeable patterns were observed for all analyses with the exception of the species relationship to modeled threats. The Cubera Snapper did not typically show up in areas that were considered coastal development or marine-based threat areas. This relationship speaks to the species itself as it indicates that certain contaminants that may be introduced via shipping or coastal development are potentially harmful to the species in particular. It could also be hypothesized that the marine-based threats stemming from increased ship traffic could have led to mangrove clearing or an increase in turbidity making the mangroves uninhabitable for juvenile Cubera Snapper.

4.1.7 Red Lionfish

The only invasive species surveyed in this study was the Red Lionfish. This species has been spreading across the Gulf of Mexico at an alarming rate since being introduced in 1985 (Betancur-R et al., 2011). The IDW, time series, MPA effectiveness, and percentage of sightings analyses all indicate an extremely rapid invasion of the species across the Belize Barrier Reef. Up until 2007 the species was absent from all REEF surveys submitted in the eight prior years. 2007 marks the first surveyed sighting in Belize and results from all of the analyses indicate a dramatic increase in the abundance of Red Lionfish within the reef. An observation can be made that the trend of surveys and average abundance for the species appear to begin in the north and out on the atolls and are slowly creeping down the coast. This is interesting but does not necessarily mean that the species is not found below the furthest reported REEF sighting in the Caribbean. The species is also abundant far further south in Honduras and the lack of data in southern Belize may be due to currents or other implications yet to be determined (Betancur-R et al., 2011).

The Red Lionfish is seen as an extreme threat to many aspects of the biodiversity of coral reef systems, often interrupting the food chain and reproducing at a rapid rate. The threat score analysis provides a good example of the species resiliency when looked at in comparison to other methods that show the spread of the population such as the time series and IDW analysis. Comparing the threat score analysis results with the locations in which the Lionfish sightings and abundances appear shows that despite several survey locations being categorized as a highly threatened area, the species still tends to appear in relatively high abundance.

With Red Lionfish being one of the most widely recognized invasive species in shallow water reef environments, several organizations in Belize are actively seeking out methods to control and hopefully reduce and eradicate the population. Means such as lionfish roundup fishing tournaments to see who can bring in the most fish are being employed as well as no restriction on the fishing methods or catch limits for the species. The Red Lionfish is a well-known invasive species to the locals who often choose to spearfish for the species as sport, as well as for the added benefit of it being a table fare delicacy to many. Diller et al. (2014) and Frazer et al. (2012) touch upon the rapid spread of the species and potential eradication methods to aid in removal and depletion of the species over time. Opposite to that of the threatened species, continued efforts such as roundup tournaments and no fishing restrictions may lead to the spread being potentially controlled although not fully eradicated from the reef due to the overwhelming resiliency the species maintains (Albins et al., 2013).

4.2 Research Objectives

Throughout this research, several objectives were targeted in order to understand the relationship between how using fish survey data from REEF can be analyzed spatially in order to understand threatened and invasive fish species on the Belize Barrier Reef and the relationship of their distribution to the environmental threats posed to the barrier reef system. Each objective will be briefly addressed here. The main research question and subsequent objectives were as follows:

How do at risk and invasive fish populations vary in space and time as related to environmental threats on the Belize Barrier Reef?

- Objective 1: Analyze the sighting frequency and abundance of fish species in space and time
- Objective 2: Examine the spatial relationship of fish species to modeled environmental threats

- Objective 3: Assess the effectiveness of marine protected areas in relation to fish abundances and distribution
- Objective 4: Investigate the timing and spread of invasive Red Lionfish

4.2.1 Objective 1: Sighting frequency and abundance of fish species in space and time

Changes in species distribution over a period of time were analyzed in GIS using a variety of different methods to understand patterns spatially. Using the percentage of sightings by year initially, followed by time series and IDW analyses, fish data were able to be interpreted across time and space in order to draw conclusions on the general health of a species across a large area such as the Belize Barrier Reef. The various species targeted throughout this research served as indications of how effectively changes across a large area can be visualized.

Results of these analyses tell a story and offer explanations for changes in patterns over time. Declines in survey entries for Goliath Grouper, Hogfish, and Nassau Grouper can be further looked at with time series and IDW analyses to try to distinguish where exactly each species is suffering. It is also effective on the other end of the spectrum to understand increases in activity for species such as the Queen Triggerfish, Mutton Snapper, and invasive Red Lionfish to explore the implications surrounding their success. From analyzing both the time series and IDW analyses in conjunction with temporal pattern seen in the survey percentages, most of the species showed higher abundance values in the outer atolls and reefs which may indicate a more sustainable habitat for the threatened species. Species that displayed no noticeable spatial distribution pattern or high concentrations in the north experienced a general decrease in survey entries.

4.2.2 Objective 2: Spatial relationship of fish species to modeled environmental threats

The distribution of sightings and fish abundances examined in the time series and threat score analyses were used in conjunction with modeled threats to infer relationships between the two analyses. Species concentrations and distribution changes over time were compared to threat data in order to look for potential threats that may be harmful to a particular fish species. In conjunction with the time series analysis, it was found that both the Queen Triggerfish and Mutton Snapper data generally plotted in areas away from modeled marine-based threats. Cubera Snapper species concentrations did not show up near areas threatened by coastal development or marine-based threats. These findings can infer species vulnerabilities and correlate with individual species lifestyles. Increased stressors, such as physical alterations to bathymetry through dredging have the ability to alter the substrate and seagrass habitat each of these species rely on. This may point to why these species are found further away from such threats. Nassau Grouper also revealed implications of the relationship of this species to ongoing threats to the environment. As the most recent species classified as endangered in Belize, the decline in survey entries since 2012 was compared to the threat score map which resulted in it being the only species showing up in high threat severity areas which may be contributing to its apparent recent decline. Having the ability to understand the impact environmental stressors are having to fish through sighting and abundance data can be used as an invaluable tool to pinpoint the most immediate threats to certain species.

4.2.3 Objective 3: Effectiveness of marine protected areas in relation to fish abundances and distribution

Marine protected areas are becoming a vital revitalization tactic for many threatened marine species across the globe. The effectiveness of MPAs in this study was analyzed using species abundance in pre-MPA and post-MPA 5-year datasets. It was found that the implementation of MPAs is having a positive impact on several of the threatened species on the reef. The Nassau Grouper, Queen Triggerfish, and Hogfish all experienced a sharp increase in abundance data within the newly designated MPAs in the five years after their induction, at least in certain locations. Of the MPAs, the “no-take” zones showed the most notable increases in concentrations of the species. The Hol Chan Marine Reserve and southern portions of both Glover’s Reef and Turneffe Atoll in particular all experienced increases in species abundance for the previously mentioned species. Although these three species showed the most noticeable positive impacts of the MPAs, it was also found that none of the species in this study showed a major decline within the MPAs over the time spans prior and post 1998. These results confirmed the notion that MPAs can have an immediate positive effect on the sustainability and health of fish populations in these areas.

4.2.4 Objective 4: Timing and spread of the invasive Red Lionfish

The spread of the invasive Red Lionfish was analyzed in GIS using the same IDW, time series, and survey percentage by year analyses. When the REEF abundance data was plotted for Red Lionfish, in order to say there is a definite spread in the species over a period you need to see an increase in sightings or abundance as time passes. In the case of this study, lionfish were not noted in surveys until 2007 where in the following years leading up to 2015 more and more sightings were being plotted each year leading to the conclusion that the species population was therefore growing, and also extending its range south. The survey percentage analysis confirmed these findings by revealing a rapid upward trend in the number of surveys that included lionfish sightings per year and the other analyses combined further indicated increasing abundances.

4.3 Limitations

It is important to realize some of the potential issues that may arise when using the datasets obtained from both REEF and CZMAI when drawing conclusions. First, the REEF dataset is based off of a citizen science platform in which many individuals record their observations during dives and submit them to a massive database where it is included with other submissions. Although the overall methodology to recording and submitting dive survey data is relatively consistent and the REEF database is a recognized source of accurate species and abundance data as a proxy for fish populations, it is possible that variation exists in the quality of submitted surveys whereby some are more accurate than others.

In order to combat that, expert surveys were thoroughly cross referenced with novice submissions to check for relative consistency and accuracy before incorporating all of the submitted surveys into a spreadsheet. REEF ranks surveyors' experience levels by either novice or expert. Novice surveyors are level 1-3 classifications, while expert surveyors are in level 4-5. These levels are gained by taking and passing quizzes as well as the recording the number of surveys entered into the database. Novice surveys were grouped together with expert surveys and compared side by side to make sure no high or low abundance anomalies were added to the database used in the analyses. Of the thousands of surveys, only three surveys were thrown out due to general inconsistency which speaks to the overall consistency and accuracy of the data.

Since the REEF dataset is based on a citizen science platform in which members submit reports, the amount of surveys completed at a given locale has the potential to vary over time. Although this has the potential to skew numbers, sighting frequency reports for species appeared to be consistent despite a variance of submissions in a given year. With the REEF database being driven by citizen science, the amount of surveys per year that were submitted had the potential to vary greatly due to a wide variety of reasons. Anything from travel expenses, weather, natural disasters, and so on may have had an impact on the number and consistency of surveys from year to year. The number of survey entries per year ranged from the lowest of 14 in 1998 to the highest being 410 in 2006. The surveys and data were standardized for the percentage of surveys per year analysis, but it is possible that there were low counts of surveys in particular locations during a given year that may have potentially biased the results. However, the fluctuation in the number of submitted surveys per year should not have an impact on the trends seen in the survey percentage per year analysis due to the results being standardized (Table 2). In particular, the years of 1997, 1998, 1999, and 2002 showed the lowest number of surveys, while the years of 2000, 2003, 2006, and 2014 showed the highest number of surveys. The average number of survey species entries per year was 6,619 and the average number of surveys per year was 152. Similarly, calculations of mean abundance for GIS analyses helped mitigate concerns regarding low survey numbers or variability in reports by citizen scientists.

The data collected on the Goliath Grouper was extremely limited. Of the 145,622 entries of all species documented in the study area from 1994 to 2015, Goliath Grouper was only represented in 17 (Table 2). This has the potential to be interpreted in a couple different ways. First, it could mean that the species population is in an extremely endangered state and the low number of sightings is an accurate representation on how few Goliath Grouper are left on the Belize Barrier Reef. The low number of sightings represented in the surveys could also be seen as a potential limitation in the sense that the species was just not relevant in many of the areas in which the surveys took place and due to the habitat of the survey locations not being sufficient for the Goliath Grouper. However, due to over 300 dive sites logged in the surveys it is unlikely that the preferred habitat of the species would not be present in at least a portion of the dive sights. The percentage of sightings by year analysis poses issues with the lack of Goliath Grouper data, but it potentially represents an accurate conclusion in the trend of the species (or reflects issues in sampling rare species). Due to the overall number of surveys per year being so low, it is possible that the final nine years that indicate a zero in the number of surveys with Goliath Grouper sightings could also coincide with actual low abundances of this fish. Therefore, it is important to understand that the Goliath Grouper population on the Belize Barrier Reef is extremely low based on the survey data, may or may not be considered on a downward trend, and further study and immediate action is needed to clarify the critical state of this species.

Abundance values obtained from the REEF database were changed to average abundance scores for the purpose of this study and to avoid overlapping spatial data within GIS. This can create an issue since the average abundance values are no longer able to be referenced to the abundance scores designated by the REEF database. However, similar studies with REEF abundance data transferred into this average abundance format can be seen in Jeffrey (2004) and Pattengill-Semmens (2006). Rather than having whole number scores, the average abundances were calculated and often fell in between numbers which can lead to imprecise abundance values. These new average abundance values should be inferred and taken into consideration when looking at the abundance results from analyses in which they were used such as the IDW, time series, and MPA effectiveness analyses.

It is also important to note that spatial data compiled from CZMAI used in the Belize Coastal Threat Atlas was based on a report from a single year. Although the data was from the most recently published Belize Coastal Threat Atlas produced in 2005, it does not show changes in the threats over a period of time. Nothing in particular was noted to have seen a significant change in the overall threat projections set in place by CZMAI, but it is possible that the threats could have been mapped very differently prior to the 2005 Belize Coastal Threat Atlas or afterward. However, for the purpose of this study, having the threat data from the most recent survey allowed for interpretation based on relatively current conditions. Although, having the CZMAI threat data from multiple years including those near the beginning of the REEF data in 1994 may have been useful for further analysis, threat data obtained from WRI's most recent publication that used CZMAI data was used throughout this research in order to understand the present state of the threats to reef habitats. It can potentially be inferred that with the increase in industry, tourism, and development since this study's 1994 start date that several of the mapped threats such as the marine-based and coastal development threats may have been less severe due to the gradual increase of both coastal development and shipping over the years but are perhaps even more problematic over the last 10 years.

For the purpose of this study, the marine protected areas spatial dataset provided by CZMAI was altered from its original state in the publication in order to simplify the interpretation of the data. In the Belize Coast Threat Atlas spatial dataset received from CZMAI, the MPAs contained additional classifications for marine protected areas outside of the basic "general use" and "no take" designations. In order to have a more streamline analysis and interpretation, the Belize Coastal Threat Atlas published in 2005 was referred to and the symbology for the MPAs was transferred into newer shapefiles. Rather than having the marine protected areas classified in a multitude of different designations that were unclear in the literature, I classified each marine protected area as either "general use" or "no-take" based on the 2005 Belize Coastal Threat Atlas, as these were still understood as the overlying classification of the areas. Due to the MPA effectiveness spatial query analysis only using the survey locations within all MPAs regardless of classification, this change in symbology should not have an effect on the overall outcome since all of the designated MPAs locations, areas, and borders were unchanged, and only the symbol classifications were altered.

Another limitation lies in the threat score analysis. The threats were not weighted against each other therefore it would be inferred that all threats are weighted equally which may not be the case. Weighting the threat levels would be indicating that certain threats have more of an impact on the fish species studied than others. Had this study been focused on one species in particular where the individual species vulnerabilities could potentially lead to threats being weighted, it may have been appropriate. However, for the purpose of this work and because several different species are being investigated here, threats were all weighted equally against each other.

4.4 Continued Work

The work conducted in this thesis will continue with several more statistical and analytical methodologies employed, as well as results sharing with several organizations in Belize. In correspondence with the percentage of sightings by year analysis, options might include a Kendall's Tau statistical correlation to be conducted in order to rank quantity correlations and trends as well as the Mann-Whitney U test on the MPA effectiveness analysis. One of the main goals of this research was to be able to create an easily attainable and widely understood spatial analysis of the correlation between threatened and invasive species. Creating maps with these multi-variable approaches and being able to share results with individuals allows for the growth of both research and knowledge on the subject with applications for conservation measures. Belize and its barrier reef are at risk to many stressors that are increased by the continued rise in development and tourism. In sharing the results and findings with various organizations and groups in Belize, as well as having it readily available to the public for viewing, serves as a model that can be applied in other settings, particularly in using a citizen science database such as REEF when data on fish populations are challenging to obtain. This work demonstrated the power of citizen science data and GIS applications, as others have done in a similar way in studying spatial distributions of the invasive Red Lionfish using data from citizen scientists (e.g., Scyphers et al., 2014). Upon conclusion of this work, it is important to share the results with Belizean organizations and individuals in an effort to better understand the continually changing conditions on the reef as well as to use the this information in creating and modifying management plans for the future.

5 SUMMARY AND CONCLUSIONS

Belize and its adjacent barrier reef are experiencing a rapid increase in the amount of human traffic due to the appeal to vacationers across the world. The subsequent influx of income to the economy is being redistributed back into the country via continued development along the coast and across the barrier reef system. This comes with an increase in boat traffic and ships in both the commercial and tourism based boating practices centered on fishing and water transportation. Development and agricultural practices have the potential to leech into the groundwater and be carried along inland rivers that eventually flow into the ocean. All of which can lead to potentially threatening conditions to the delicate barrier reef system inhabited by many unique and important species to the reef's overall health. Using citizen science based REEF data in a spatial setting with GIS has the potential to be organized, plotted, and interpreted by many organizations dealing with both the health of a coral reef system, as well as fisheries management in order to make important decisions regarding the management tactics needed to maintain a thriving barrier reef system.

The analyses conducted in this research aim to track the spatial distribution of species over time which indicated a steady decline of several threatened species. Time series and IDW analyses incorporating both REEF survey data and CZMAI threat data allowed for a look into species abundance trends over time and the possible implications of how certain species may be reacting to threats to the reef. Goliath Grouper and Hogfish exhibited sharp declines while the invasive Red Lionfish population exploded. Results concluded that the overall population of some species such as the Queen Triggerfish and Cubera Snapper may be remaining relatively consistent but on a recent gradual upward trend. A decline in the Goliath Grouper, Hogfish, and recent downward trend in the Nassau Grouper has the potential to be connected to several threats to the reef system while an increase in Mutton Snapper may be connected to the positive impact marine protected areas are having throughout the reef. The ability to understand the most vulnerable fish species and their overall population health within a given ecosystem can act as an important indicator to the health of the reef system as a whole. It was evident from the results that the threatened species react to stressors to the environment. Coastal development and marine-based threats in particular seem to lead to changes in spatial distribution. MPA effectiveness concluded that marine protected areas are having a positive impact on several species such as the Nassau Grouper, Queen Triggerfish, and Mutton Snapper in several locations and have the potential to lead to a gradual recovery in the growth of threatened populations of fish. Findings such as these are important to plan for future sustainability of such species. Red Lionfish results concluded a drastic rise in abundance across the reef. Although lionfish were known to be a threat, the magnitude of the data clearly indicates the intensity in which the population is growing. Trends studied over space and time in GIS for multiple species highlighted both the various threats and positive influences that impact these reef habitats. The integrated approach with the incorporate of citizen science data is vital to understanding these complex ecological interactions and what can be done to preserve threatened biota in the future.

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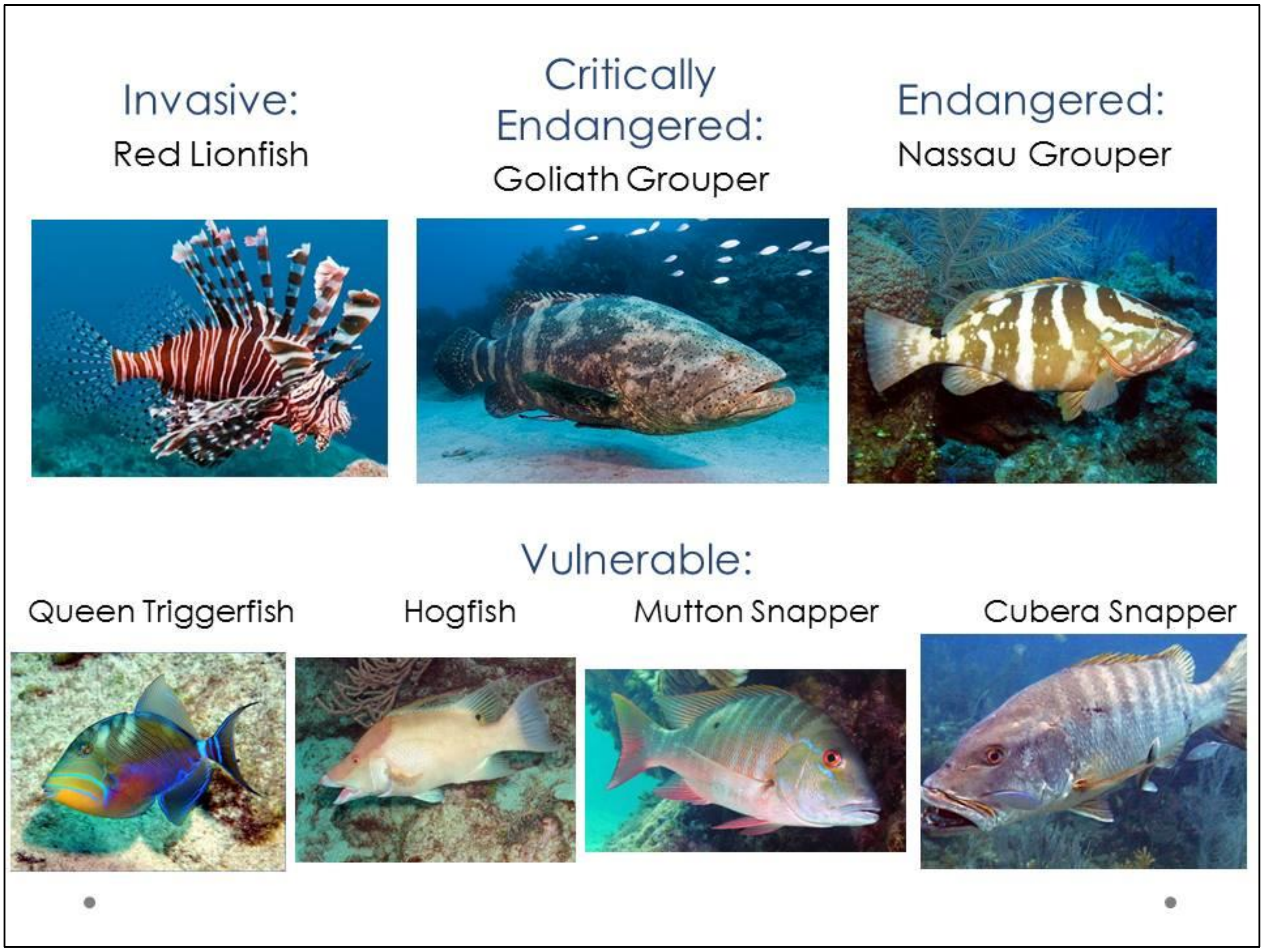
APPENDICES

Appendix A:



Appendix B:

ID	Location	Longitude	Latitude	NG99	NG00	NG01	NG02	NG03	NG04
55040030	Abyss West (Sandbore Caye)	-87.499333	17.4606667	0	0	0	0	2	0
55030066	Alfredo's	-87.78	17.48	0	0	0	0	0	0
55030063	Alpine Wall	-88.0774	16.9556667	0	0	0	0	0	0
55030015	Al's Hideout (Blackbird Caye)			0	1	0	0	0	0
5501	Ambergris Cay to Cay Caulker			0	0	0	0	0	0
55030017	Amberhead	-87.9454	17.3736	0	0	1.67	0	1.67	0
55010024	Amigo's Wreck	-87.983	17.8275	0	0	0	0	1.14	0
55030061	Anchorhead (Turneffe Island, West Side)			0	0	0	0	0	0
55050032	Angelfish Wall			0	1	0	0	0	0
55010020	Annie's Fannie (St George's Cay)			2	0	0	0	0	0
55040062	Aquarium (Halfmoon Caye)			0	0	0	0	0	0
55040009	Aquarium (Long Caye)	-87.604883	17.2262333	1	1.93	1	2	1.17	0
55040061	Back Reef - Long Caye	-87.598967	17.2237333	0	0	0	0	0	0
55050004	Baking Swash (West Cut)	-87.858	16.7996667	0	0	1.5	0	0	0
55050028	Barrel Sponge Reef (Middle Caye)	-87.814	16.736	0	0	1.33	0	0	0
55010016	Barry's Bush (St George's Cay)			0	0	0	0	0	0
55010034	Basil Jones			0	0	0	0	1.16	0
55	BELIZE	-88.783333	17.6666667	0	0	0	0	0	0
5506	Belize City			0	0	0	0	0	0
55010042	Belizean Shores Resort			0	0	0	0	0	0
55050020	Beverly's Aquarium	-87.7895	16.751	0	0	1	0	0	0
55030059	Black Pearl (Turneffe Island, West Side)	-87.941433	17.383	0	0	0	0	0	0
55030014	Blackbird Cut (Blackbird Caye)			0	1	0	0	0	0
55030087	Blackbird Pier Snorkel			0	0	0	0	0	0
55010051	Blair (St. Georges Caye)	-88.044683	17.5053	0	0	0	0	0	0
55040003	Blue Hole	-87.53475	17.3148333	0	0	0	0	2	0
55010037	Boca Chica	-87.975333	17.8518333	0	0	0	0	1.87	0
55010028	Boca Ciega	-87.966	17.877	2	0	0	0	1.5	1.5
55010005	Boca Del Rios	-87.944167	17.87	0	0	0	0	0	0

Appendix C:

	A	B	C	D	E	F	G	H
1	ID	Location	Longitude	Latitude	Date	Species	SpeciesID	Abundance
2	55040030	Abyss West (Sandbore Caye)	-87.49933333	17.46066667	1994	Mutton Snapper	195	0
3	55030066	Alfredo's	-87.78	17.48	1994	Mutton Snapper	195	0
4	55030063	Alpine Wall	-88.0774	16.95566667	1994	Mutton Snapper	195	0
5	55030015	Al's Hideout (Blackbird Caye)			1994	Mutton Snapper	195	0
6	5501	Ambergris Cay to Cay Caulker			1994	Mutton Snapper	195	0
7	55030017	Amberhead	-87.9454	17.3736	1994	Mutton Snapper	195	0
8	55010024	Amigo's Wreck	-87.983	17.8275	1994	Mutton Snapper	195	0
9	55030061	Anchorhead (Turneffe Island, West Side)			1994	Mutton Snapper	195	0
10	55050032	Angelfish Wall			1994	Mutton Snapper	195	0
11	55010020	Annie's Fannie (St George's Cay)			1994	Mutton Snapper	195	0
12	55040062	Aquarium (Halfmoon Caye)			1994	Mutton Snapper	195	0
13	55040009	Aquarium (Long Caye)	-87.60488333	17.22623333	1994	Mutton Snapper	195	0
14	55040061	Back Reef - Long Caye	-87.59896667	17.22373333	1994	Mutton Snapper	195	0
15	55050004	Baking Swash (West Cut)	-87.858	16.79966667	1994	Mutton Snapper	195	0
16	55050028	Barrel Sponge Reef (Middle Caye)	-87.814	16.736	1994	Mutton Snapper	195	0
17	55010016	Barry's Bush (St George's Cay)			1994	Mutton Snapper	195	0
18	55010034	Basil Jones			1994	Mutton Snapper	195	0
19	55	BELIZE	-88.78333333	17.66666667	1994	Mutton Snapper	195	0
20	5506	Belize City			1994	Mutton Snapper	195	0
21	55010042	Belizean Shores Resort			1994	Mutton Snapper	195	0
22	55050020	Beverly's Aquarium	-87.7895	16.751	1994	Mutton Snapper	195	0
23	55030059	Black Pearl (Turneffe Island, West Side)	-87.94143333	17.383	1994	Mutton Snapper	195	0
24	55030014	Blackbird Cut (Blackbird Caye)			1994	Mutton Snapper	195	0
25	55030087	Blackbird Pier Snorkel			1994	Mutton Snapper	195	0
26	55010051	Blair (St. Georges Caye)	-88.04468333	17.5053	1994	Mutton Snapper	195	0
27	55040003	Blue Hole	-87.53475	17.31483333	1994	Mutton Snapper	195	2.67
28	55010037	Boca Chica	-87.97533333	17.85183333	1994	Mutton Snapper	195	0
29	55010028	Boca Ciega	-87.966	17.877	1994	Mutton Snapper	195	0
30	55010005	Boca Del Rios	-87.94416667	17.87	1994	Mutton Snapper	195	0
31	55010035	Bocalar Chico Shallow	-87.82416667	18.135	1994	Mutton Snapper	195	0
32	55010011	Bruce's Column (St George's Cay)			1994	Mutton Snapper	195	0
33	55030085	Calabash Cut	-87.80445	17.27825	1994	Mutton Snapper	195	0

RL | GC | NG | QT | H | MS | CS