Multitemporal Assessment of Coastal Erosion: Case studies from the Gulf of Mexico, the Atlantic Ocean, and the Mediterranean Sea

by

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A thesis presented to the Honors College of Middle Tennessee State University in partial fulfillment of the requirements for graduation from the University Honors College

Spring 2021

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ABSTRACT

Over two billion people live in coastal regions worldwide. With such a large volume of people living near the ocean, it is important to understand how coasts are changing over time. The goal of this study is to explore how barrier islands undergo coastal erosion and how their shapes change in response. Barrier islands line mainland coastal areas and are their first line of defense from open waters. In this study, satellite images of Horn Island from 1984 to 2016, Cumberland Island from 1988 to 2019, and Venice Lido from 1985 to 2019 were carefully traced. The traced images were processed in order to measure changes over time in their shape and size and indicated that Horn Island's area decreased by .42% each year of the study, Cumberland Island's area decreased by .29% each year, and Venice Lido increased by .16% per year. Understanding the magnitude and behavior of change can lead to an understanding of the mechanisms driving the change. With sea levels projected to continue rising, it is imperative to offer information on how coasts are predicted to change in response to sea level rise to those that live near them.

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INTRODUCTION

Worldwide, there are approximately 2,149 barrier islands that line continental landmasses (Volland, 2011). Barrier islands are elongated sand deposits that are oriented roughly parallel to the mainland (Olsen). Separated from nearby mainland by a lagoon or salt marsh, these unique features serve to provide a buffer between hurricanes and the ocean in general and the landmasses and marshes the islands protect. As hurricanes move over land, they slow down as they encounter friction from the land's surface and lose moisture from being over dry ground (NOAA,1999). This means that barrier islands can be the catalyst for lowering a hurricane's intensity before it can reach the mainland, which are often more populated than the islands. In fact, about 94 million Americans live on America's coasts, with about two-thirds of that population living on the Gulf of Mexico and the Atlantic coast, both of which are prone to tropical storms (Cohen, 2019).

Barrier islands are play an important ecological role as they are home to diverse species. In the United States, barrier islands offer more varieties of coastal birds than any other ecosystem (Olsen). Also, the marshes that barrier islands shelter from tropical storms are frequently home to many different types of marine organisms, so barrier islands are essential to conservation.

Barrier islands are also important in that they can be a tool for gauging climate change and understanding sea level rise. Sea level rise is of increasing concern as global temperatures have been trending upward over the last century (Shaftel et. al., 2021). Barrier islands may reflect those changes in different ways as it causes some islands to be destroyed and others to be created. Creation of barrier islands can occur on coasts where sea level rise results in the formation of shallow bays that can precipitate barrier islands at the bay's mouth (Volland, 2011). Barrier islands may be destroyed, however, when islands are flooded, and accelerated erosion occurs.

The purpose of this study is not necessarily to conclude that sea level rise will result in increasing erosion or accretion of barrier islands and that this could be representative of all coasts. This study should be seen as a tool for the scientific community to build upon and compare to other studies in an effort to understand how the mechanisms of climate change and sea level rise may affect our coasts. There are various studies in place that explore the coastlines of barrier islands all over the world, but it is important that my fellow scientists have as much information from as many different islands as possible in order to get a comprehensive understanding of the forces at work on the islands. The objective of this study is to process satellite imagery of coastlines in three distinct coastal regions to measure rates of coastal erosion.

The first island that I chose to examine was Horn Island, which is off the coast of Mississippi, United States and is located in the Gulf of Mexico. This island is a designated national seashore by the National Park Service, so it is of particular interest to scientists studying coastal erosion because it is uninhabited and is monitored regularly by the National Park Service. Studies that other scientists have done on the island and surrounding islands include using LiDAR data compiled by the National Oceanic and Atmospheric Association (NOAA) to calculate sediment volumes, elevation, shoreline positions and area from 2004 to present (Gremillion, 2019). LiDAR is a remote sensing technique that uses pulsing light beams to measure variable distances from LiDAR imaging equipment in the air to earth's surface (NOAA). Other scientists have relied on

GIS, or geographic information systems to process images of Horn Island and its surrounding islands in order to understand how the perimeter, area, and orientation have changed in the past (Morton, 2007). The National Park Service constructs a topographic profile of Horn Islands and its surrounding islands each spring in order to monitor any changes in the shape and topography of the shores. This helps the National Park Service know when beach nourishment is needed (Bracewell, 2017).

Cumberland Island was the next island that was studied. Like Horn Island, Cumberland Island is a national seashore. It is located on the Atlantic coast of Georgia, United States. Scientists supported by the National Park Service have studied this island by mapping its coastline at five distinct sites using real-time kinematic and global positioning system technology (McDonald and Gregory, 2018). Real time kinematic, like the global positioning system involve deriving images from satellites. Scientists who have studied this island seem more concerned with the back barrier erosion going on at this site than the ocean side erosion that is occurring as fluvial processes by way of the St. Marys River, Crooked River, and Satilla River have a prevalent influence on the location.

The final site that I studied was Lido di Venezia, or Venice Lido. This island is located in the Venetian Lagoon of the Mediterranean Sea off the Italian coast. This site is regularly monitored by the Italian government as unlike the other islands it is populated so it makes sense that the government would take an interest in watching for flooding which could trigger erosion. A technique called the Modulo Sperimentale Elletromeccanico, or MOSE system is being implemented to detect high tides which could result in flooding. In English that translates to Experimental Electromechanical Module (Bastionello and Balmer, 2019). On Venice Lido's inlet and those of surrounding barrier islands, there are moveable barriers that will act as flood gates which keep the Venetian Lagoon from becoming inundated (MOSE Venezia). As of right now, the technique is still being perfected but has proven effective in 2020 tests. In addition, a breakwater system is used on the island to slow water down before it can rush in and inundate the islands (Irwin, 2020).

In my study, I traced images of these sites in Google Earth. This software was helpful because it allowed me to look at these islands over the span of decades and see how the islands have changed. I processed them in GIS in order to find measurements of their area and perimeter. I was, of course, lacking a field component to my study. My original plan was to only study Horn Island and include a field trip to the site in order to better understand it. The covid-19 pandemic prevented this from happening, however. When I expanded my project to include other islands from other locations in the world, my objective changed from focusing on how much Horn Island has eroded away in the past few decades to performing a comparative analysis on three barrier islands from three distinct environments in an effort to understand the mechanisms driving their change over time. As mentioned earlier, this study is also meant to provide information to scientists who are trying to get an understanding of how barrier islands are changing in response to climate change and other anthropogenic and natural processes and what that might mean for the future of all coastlines.

STUDY AREAS

Horn Island first became of interest because the Gulf of Mexico experiences influences from both frequent hurricane activity and flow from the Mississippi River. It seems like this location would experience relatively frequent and large changes over the years due to these factors. Also, Horn Island being uninhabited, and part of the National Park Service means that any changes to the island would not be due to things like large-scale construction operations or any other manmade environmentally degrading practice. It is important to note, however that the park is open to visitors and is in proximity to the Mississippi River which transports not just sediment but any other manmade waste that makes it to the river into the Gulf of Mexico. That being said, the island is not completely isolated from human influence. The reason that Horn Island was selected over its surrounding barrier islands is because in Google Earth, its imagery had the best resolution for the longest span of time. This is important because in order to get the best results, as many clear images from as many different years as possible are needed to be able to accurately trace the island. Without precise tracing, results for changes in area and perimeter over time would undoubtedly be inaccurate.

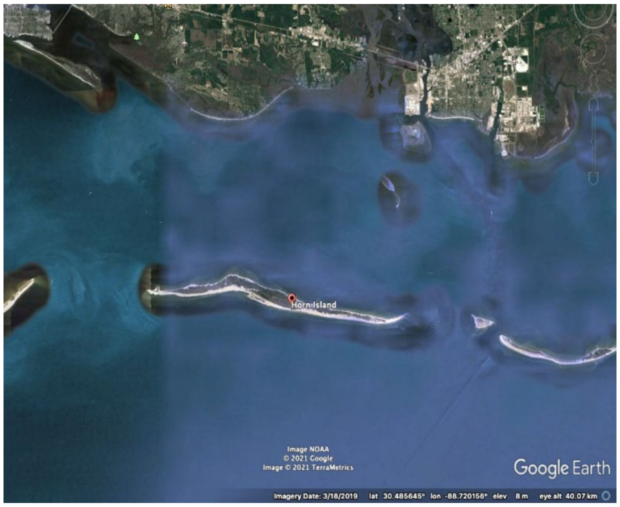

Figure 1: The image on the left depicts a satellite view of Horn Island. It is situated to the south of the Mississippi coast in the Gulf of Mexico and is one in a chain of islands. The mouth of the Mississippi River, which is not visible in the picture due to the eye altitude (zoom), is to the southeast of the island chain. The image was captured from Google Earth (2021). The image on the right is a ground image of the north shore of Horn Island. It depicts some of Horn Island's dunes which are common on barrier islands, as well as some shrubbery. The image was taken by Robert Rausch for a New York Times travel article by Jack E. Davis.

Cumberland Island was the next choice for study because like Horn Island, it is unpopulated. Surrounding barrier islands up the Atlantic coast, by contrast, were populated and were popular tourist attractions with vacation rentals and development typical of American southeastern beach towns. The island has rolling dunes on its seaside and a marsh on its back barrier side. Between these is a dense maritime forest. Although this location was not as well endowed with high resolution imagery as Horn Island, there were enough images to work with in order to come up with an overall trend for the island's perimeter and area loss over the years. What makes this site unique among the others it that one side of it is exposed to an open ocean whereas the others are open to bodies of water that are somewhat closed off from the open Atlantic. This made studying results interesting because it is changing under the influence of both the Atlantic Ocean and rivers feeding its estuary on the back barrier side.

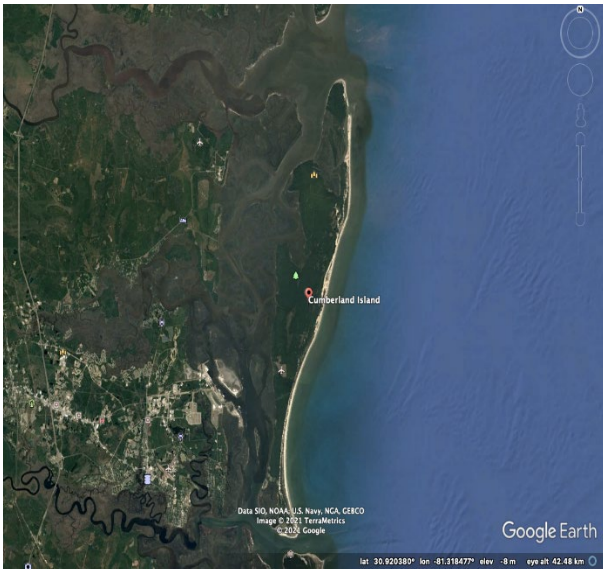

Figure 2: The image on the left is a satellite image looking down on Cumberland Island which sits off Georgia's Atlantic coast. The island sits between the Atlantic Ocean to the east and a marsh and estuary to the west. This image was captured using Google Earth. The image on the right is one I took myself in the summer of 2018. Visible are rolling dunes which give way to the shore and ocean, which are just barely visible in the distance. The roots of the plants growing out of the dunes help stabilize them.

Venice Lido was the final site of study and is located along the Venetian Lagoon within the Mediterranean Sea. In contrast to the other locations, Venice Lido is populated and has been subjected to ongoing maintenance to keep flooding and erosion under control. While long-term efficacy of intervention techniques cannot yet be known, it is interesting to examine this island for signs that efforts to maintain shores are working. Venice Lido is not unique in its location in terms of the lengths to which the Italian government goes to protect it. Its nearby barrier islands also have breakwater systems and are part of the MOSE project. I chose it over its neighbors because in Google Earth it appeared to be the largest of the islands in the system and had the most consistently clear imagery throughout the years. It also appears that there is a primitive stone wall set up in some parts of the island based on Google Earth which I believe are there to reinforce breakwaters. There were no scholarly articles or papers identifying these features. Another thing that distinguishes the Venetian Lagoon from the other bodies of water is how enclosed it and the Mediterranean Sea as a whole is from the open ocean. Horn Island is somewhat cut off from the open Atlantic, but the Mediterranean Sea is only accessible from the Atlantic Ocean through the narrow Strait of Gibraltar.

Figure 3: To the left, there is an image captured from Google Earth which shows the length of Lido di Venezia, or Venice Lido. To the northwest of Venice Lido is the island of Venice. Between Venice Lido and the mainland of Italy is the Venetian Lagoon. This group of barrier islands is located on Italy's northwest coast. The image on the right shows a section of floodgates that were implemented as part of the MOSE project. The MOSE project involves surrounding barrier islands and will be activated when tides are expected to exceed 110 centimeters (Bastionello and Balmer, 2019). The image was

taken from Angela Giuffrida's article on the MOSE project for The Guardian entitled "Venice's Controversial Barriers Prevent Flooding for the Second Time."

METHODOLOGY

The first step in this process included locating the islands on Google Earth. To see the island from year to year, the historical imagery icon was selected. Zooming in allowed for years with no imagery at that eye altitude to be removed from the historical imagery lineup. A polygon had to be constructed for each year in the intervals used for each island. Horn Island's interval was four years from 1984 to 2016, which was the last year that Google Earth had a high-resolution, zoomed-in image of Horn Island at the time of tracing. Venice Lido had polygons for every five years from 1985 to 2019 and Cumberland Island had images for every five years from 1990 to 2019 with an image from 1988 replacing one from 1985. This division of intervals is necessary because Google Earth does not have images of a decent resolution for every year at every eye altitude. The intervals were created such that they maximize the volume of clear, readable imagery for processing. This means that workable polygons cannot always be traced for every year that images exist. If polygons were created for years with poor imagery, inaccurate data could be expected to come out of the processing stage. Also, some parts of the world have historical imagery that predates others, so there are many more polygons that could be traced for those regions. A polygon is a user-generated outline of a geographic feature in Google Earth. In order to create a polygon, a user must carefully trace the boundary of the feature using the computer's mouse and keypad to create closely spaced dots. The dots form a line to outline the shape.

GIS, or geographic information systems, is a tool used for data analysis of geographic locations. An external hard drive was used to upload the polygons which were stored in compressed kmz files, which the program cannot process. In ArcMap, they were unzipped to kml files and converted to a layer, which the program can read. The layer containing the polygon was exported so that it could be projected. Projection is a tool that allows for locations on the globe, which is spherical in shape, to be laid out on a flat surface with minimal distortions. I used the Universal Transverse Mercator system to project the images. An attribute table was amended to include sections for area and perimeter which were calculated in the program using square miles and miles for units, respectively. Figures demonstrating the polygons in ArcMap are found in the Results and Discussion section of this paper.

Once these values were generated, the area and perimeter were transcribed in an excel spreadsheet. Using excel allowed for charts to be quickly and easily generated using the numbers for area and perimeter for each year that an image for each island was traced. Charts were used to generate an overall trend line as data were interpolated by the program between points representing values for years that I had measured. From there, articles and papers were analyzed in order to make sense of the trends. Trendlines and graphical representations of the data are shown in the Results and Discussion portion of the document.

This methodology is not without its limitations and sources of error. In Google Earth, not every image was traced at the same eye altitude. This means that I had to zoom in closer for some images and out farther for others. It was necessary to zoom out further for some images because there were not data for every year at every single eye altitude.

Google Earth creates a composite image using imagery from several different agencies, so one piece of the island may be captured by the United States Department of Agriculture, for example, and another piece of the island may be photographed by NASA. This causes discrepancies in factors such as the color saturation of the image. Further, the goal was to create polygons of images that were taken in the same month of the year. December was the default month for the polygons, but there were a few that did not have a December image, so the next closest month to December was used instead. The images were not of the same quality either. For example, Venice Lido's imagery was poorer until about 2000, as was Cumberland Island's in comparison to Horn Island's. Some images had extensive cloud cover and were grainy in some portions of the island, but perfectly clear in other spots. This meant that on some parts of the island where quality was poor, zooming out to get a clear enough image to trace was necessary. This meant that the dots used to outline the island were not consistently spaced throughout.

RESULTS AND DISCUSSION

Below is the table for Horn Island's data from 1984 to 2016.

Horn Island

Year	Area(mi^2)	Perimeter(mi)
Dec-84	5.69338	27.37795
Dec-88	5.548004	26.13821
Feb-92	5.3872	26.7437
Dec-96	5.335763	26.66561
Dec-00	5.323949	26.74317
Dec-04	5.302806	26.76417
Dec-08	5.050826	25.43728
Dec-12	5.011161	25.59483
Dec-16	4.879138	27.59331

Table 1: This table lists data generated from processing polygons traced in Google Earth. Processing was done in ArcMap, which is a GIS application.

The table shows a consistent decrease in area over time and a decrease in perimeter with an anomaly in December of 2016. The percentage of decrease is about 14% based off the following percentage decrease equation: -100 x [(final value-initial value)/absolute value of initial value]. This outcome was expected, as in the project's proposal stage, it seemed feasible that erosion was occurring faster than accretion due to the region's frequent exposure to tropical storms and rising sea levels. The final perimeter value being greater than the initial perimeter value may seem odd, but it is possible that perimeter can increase while area decreases, or vice versa. When geometry of a shape changes, the figure may become more elongate and grow in perimeter but decrease in area.

The trendline for Horn Island's area is shown below in figure 4:

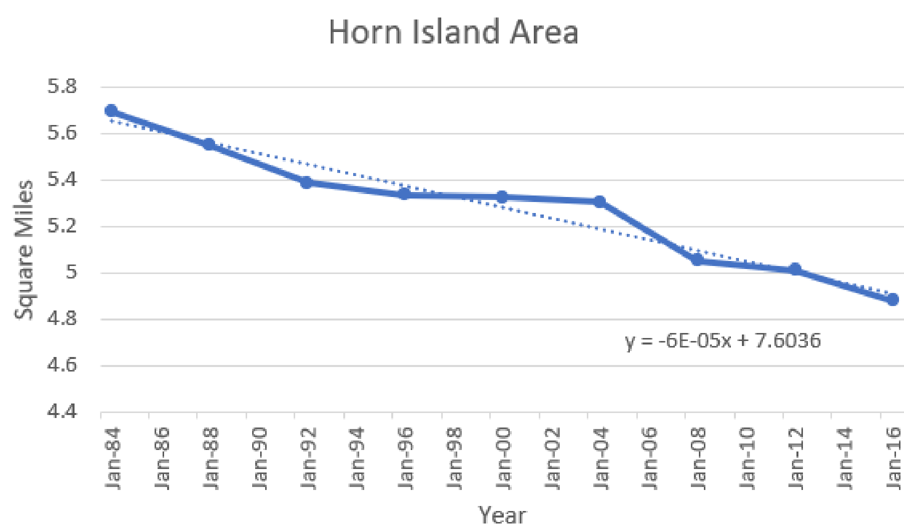

Figure 4: The data from the table are shown here in the above chart, with the year that the data were extracted being on the x-axis and the measure of the area in square miles being on the y-axis. This chart contextualizes the information. After providing excel with data for 1984, 1988, 1992, 1996, 2000, 2004, 2008, 2012, and 2016, the program plotted the points and interpolated the numbers lying between the given points.

The trendline for Horn Island's perimeter is shown below in figure 5:

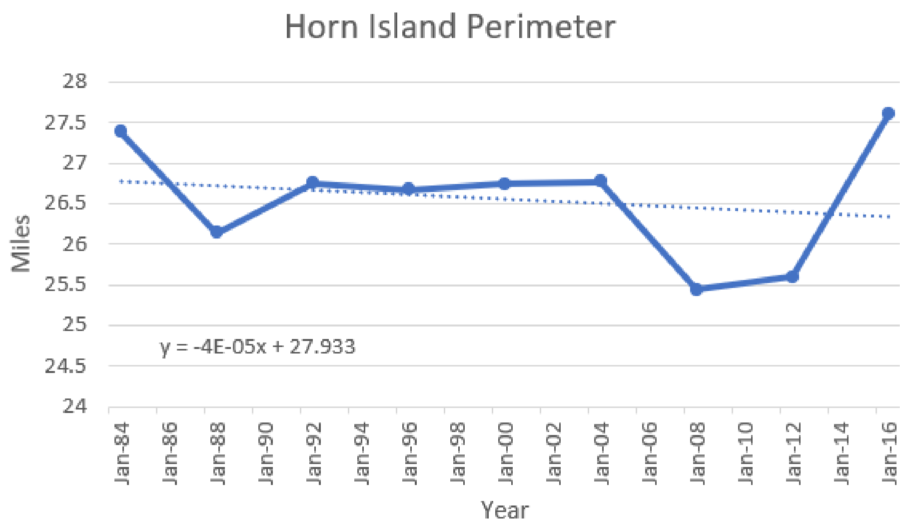

Figure 5: While Horn Island's area is obviously trending down, its perimeter is a bit harder to read. The trendline is a lot gentler and it almost appears as if the perimeter is stagnant. This means that while the size is decreasing, the shape is remaining largely unchanged.

An overlay of all the traced polygons is also available below:

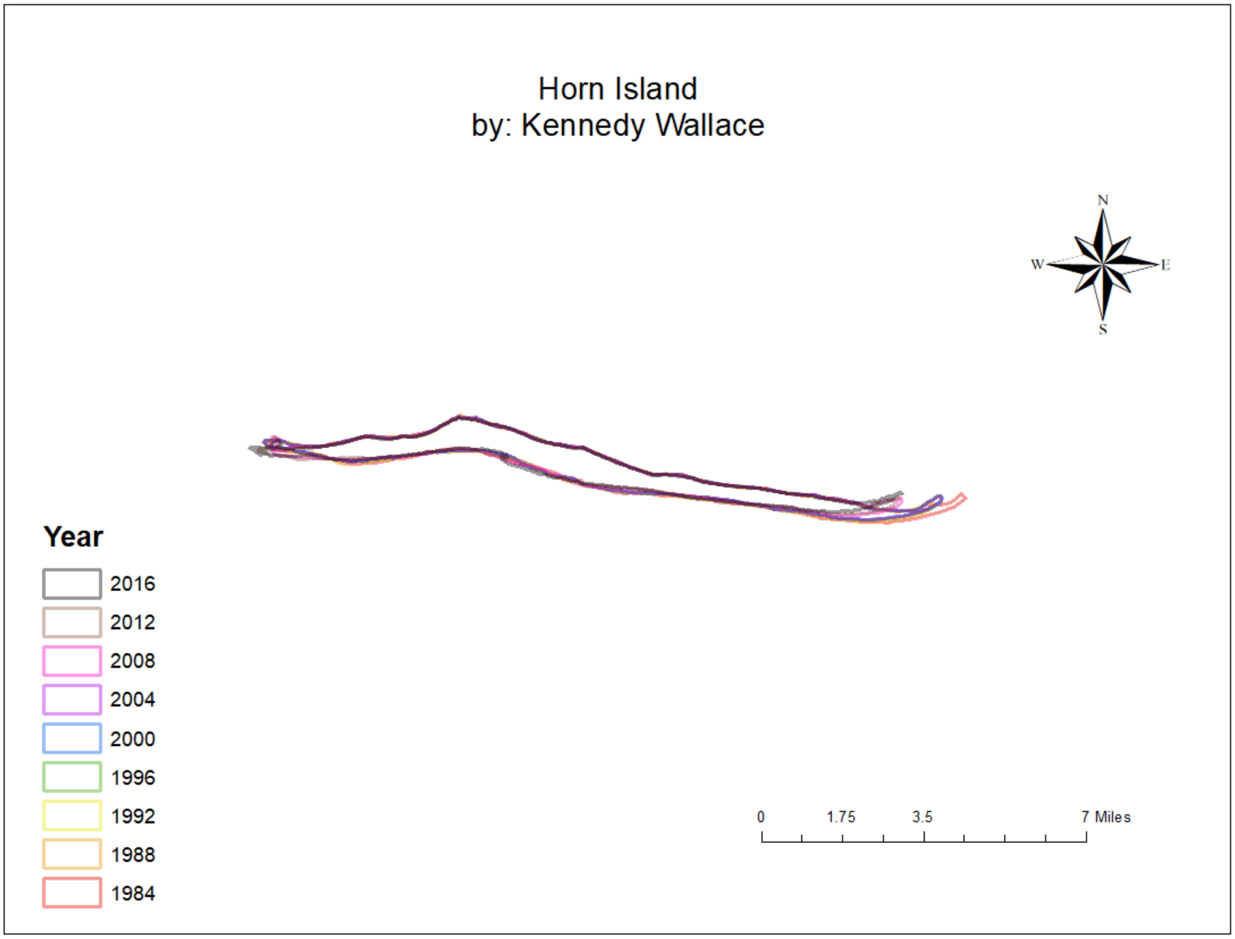

Figure 6: In ArcMap, polygons can be overlain in order to get a grasp of how their geometry has changed over time. A different color was used for each image in order to make it obvious which shape belongs to each year. This image provides tangible context to the claim that the island has shrunk in recent years.

Below is the table for Cumberland Island's data.

Cumberland Island

Year	Area(mi^2)	Perimeter(mi)
Feb-88	32.19678	45.95067
Dec-90	32.83775	48.86976
Dec-95	28.98664	54.29563
Dec-00	29.24885	54.63156
Dec-05	32.10585	53.74275
Dec-10	29.59729	55.21879
Dec-15	28.87726	57.31259
Dec-19	29.34039	53.34909

Table 2: The data in this table do not display as obvious of a trend for area as Horn Island. The numbers seem a lot more sporadic and do not follow a pattern of consistent increase or decrease.

In order to calculate the percentage decrease for Cumberland Island, the same equation that was used for Horn Island was employed for Cumberland Island. Although the data between 1988 and 2019 were scattered, there is a decrease between 1988 and 2019. The percentage decrease is measured at about 9%. This could be interpreted as the overall decrease, as clearly just by looking at the table, one could tell that the decrease did not necessarily grow every year. This was somewhat unexpected as it was hypothesized that this island would shrink by every metric over time. This is because the island is exposed to the open ocean. The Atlantic Ocean experiences a regular hurricane season in which tropical storms make landfall, so it made sense that with regular beatings from wind and rain that the island would be heavily eroded. The year 2005 sticks out a lot in this graph due to its large area in response to the prior and following intervals. This is likely due to the intense hurricane season that occurred that year. The storm surge that tropical storms carried to land that year likely resulted in large volumes of sediment being deposited on the island. This phenomenon likely overshadowed the sediment displacement action occurring due to fluvial processes on the back-barrier side of the island.

Below is the trendline for Cumberland Island's area:

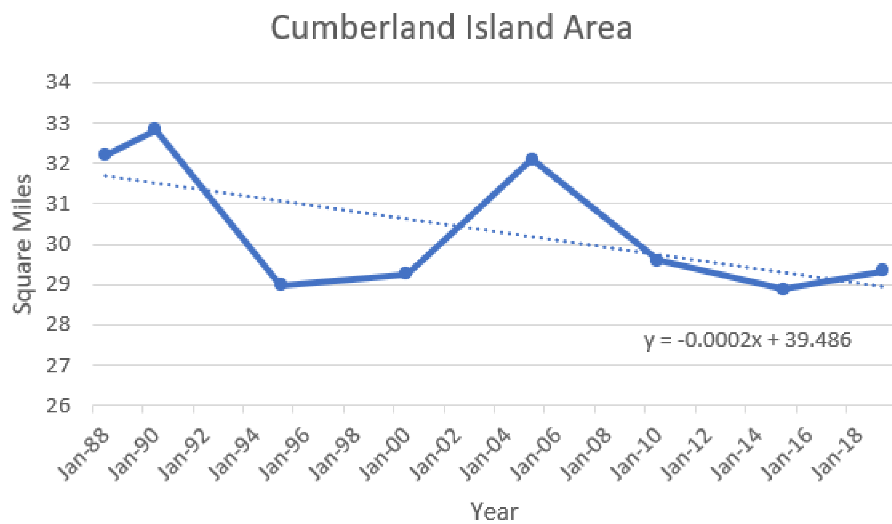

Figure 7: The graph shows a bit more fluctuation than one would expect. The spike in area in the year 2005 could possibly be due to the chaotic Atlantic tropical storm season that occurred. This could have resulted in more sediment being dumped on the island than could have been displaced by the St. Marys, Crooked, and Satilla Rivers.

Below is the trendline for Cumberland Island's perimeter:

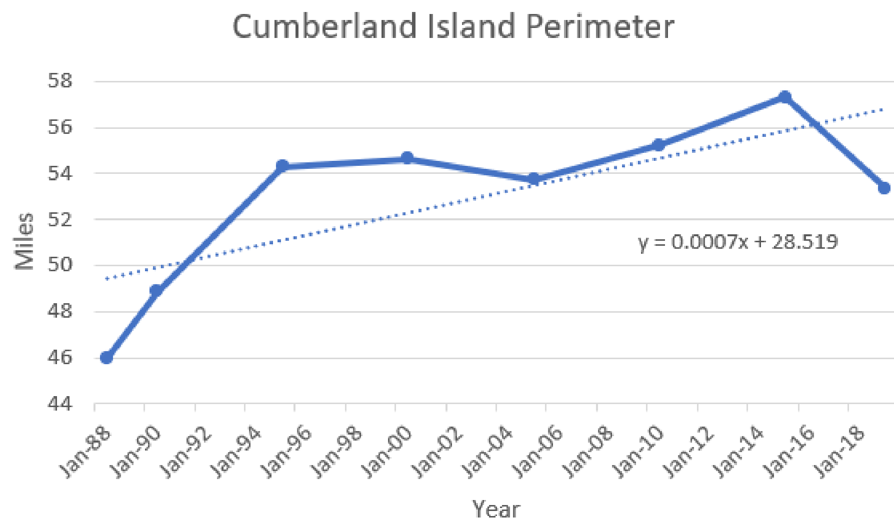

Figure 8: Unlike the curve for Cumberland Island's area, the curve for Cumberland Island's perimeter is trending upwards indicating growth in its shape despite its shrinking in area.

Included below is the overlay of all the traced polygons:

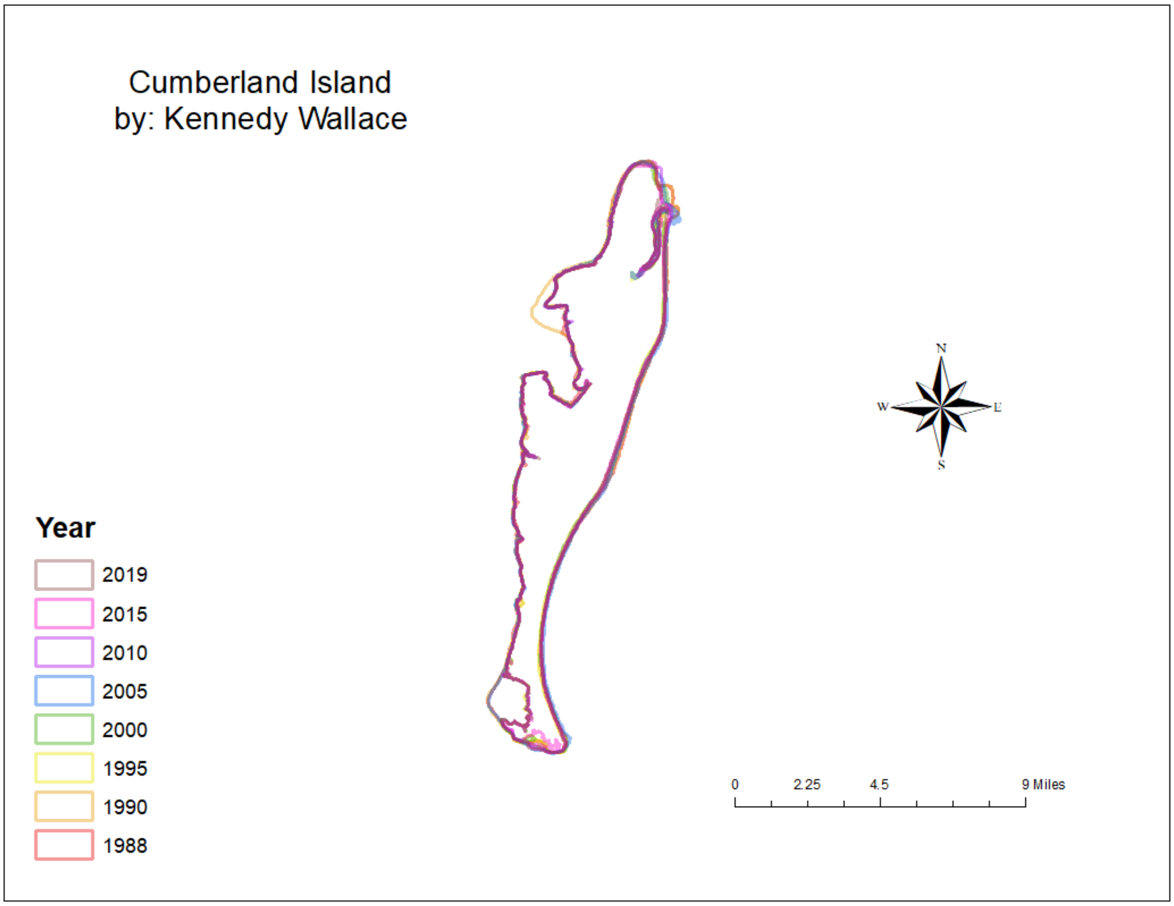

Figure 9: Again, overlain tracings of polygons provide an easy means of noting changes in the shape of the island. For the most part, the island's shape has remained consistent, but areas on the land-facing (back-barrier) side where large pieces of land appear to be missing are apparent.

Below is the data tabulated for Venice Lido:

Venice Lido

Year	Area(mi^2)	Perimeter(mi)
Dec-85	2.629982	17.21544
Dec-90	2.753424	16.9922
Dec-95	2.827742	17.27154
Dec-00	2.735002	17.37239
Dec-05	2.896109	16.98308
Dec-10	2.796887	17.60953
Dec-15	2.888328	17.63077
Dec-19	2.783163	17.53883

Table 3: Although this island shows a bit of fluctuation in its area and perimeter, it could be

noted that there is a net increase in both area and perimeter.

Venice Lido's percentage increase in size over the years is about 5.5%. You could also look at Venice Lido as having a negative percentage decrease of 5.5% in order to be able to compare it with the other two island examples. Again, this island is monitored and exists in a semi-enclosed sea. This island does not really experience the storms and disturbances that are more common to the warm, deeper waters of the Atlantic Ocean and the Gulf of Mexico. While landmasses in the Mediterranean Sea can be flood-prone, tropical storms have sudden, deep storm surges and fast winds that could be more effective at displacing sediments than simple inundation. Floods that affect the Venetian Lagoon are usually about calf-deep (Buckley, 2020) as the Venetian Lagoon's maximum depth is only 164 feet and the average depth is about 10 feet (Sorokin et. al., 1996)

Below is the trendline for Venice Lido's area:

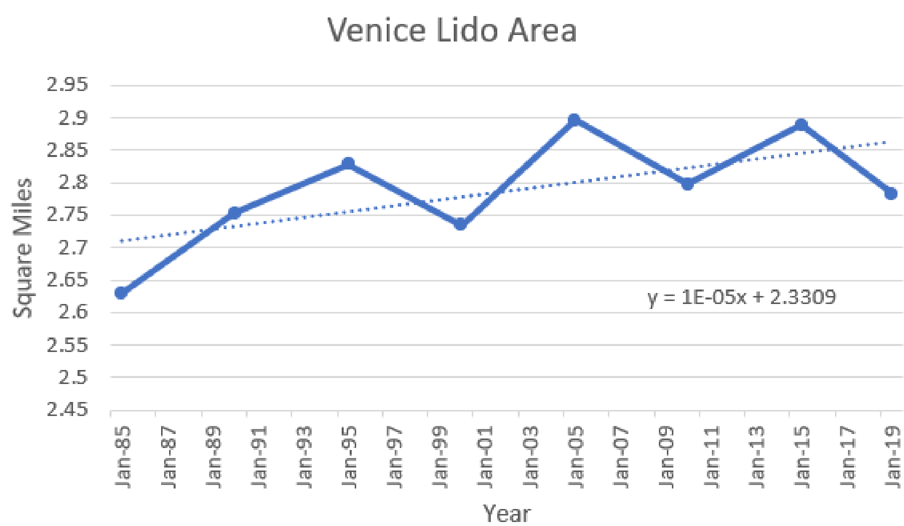

Figure 10: The trendline for Venice Lido's area is going up, indicating an increase, rather than a decrease, which occurred for the other islands. Regulation and management of this barrier system likely contributed to the slight increase in area.

Below is the trendline for Venice Lido's perimeter:

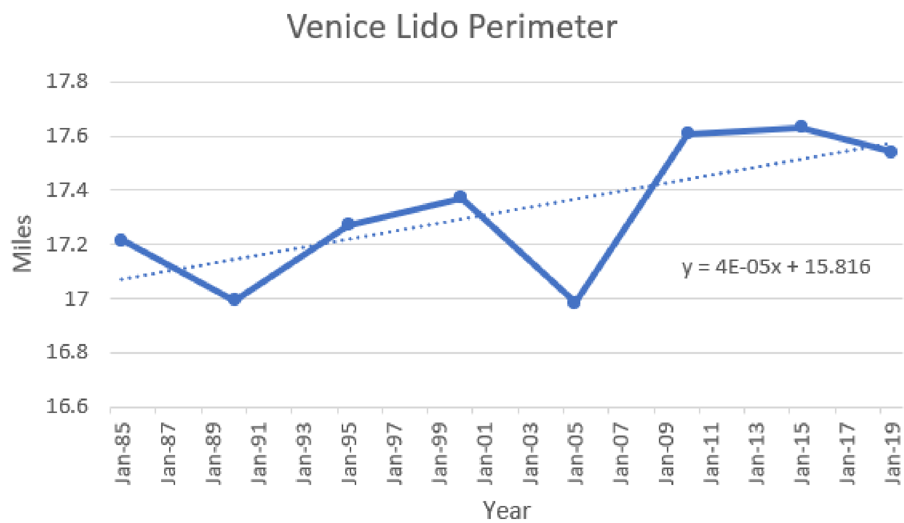

Figure 11: Like Venice Lido's area, its perimeter is also trending upwards.

The overlay of the island's polygons is shown below.

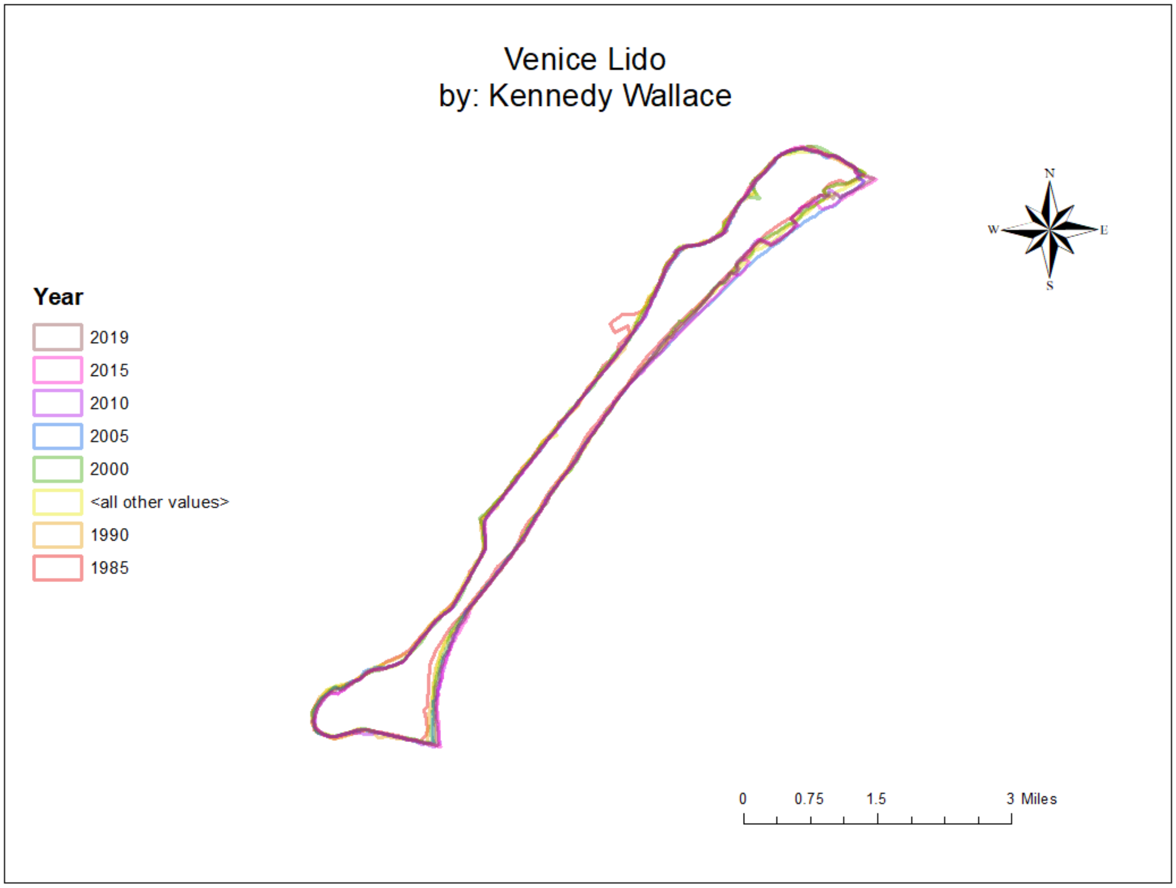

Figure 12: As is evident, the island does not appear to change much from interval to interval.

This makes sense as the net percentage increase was around 5% over the span of 34 years.

CONCLUSIONS

Horn Island and Cumberland island, which are not protected by seawalls and semi-enclosed environments have diminished over the years. Even with cautious management, however, Venice Lido's area really did not increase very much relative to the span of time that the study took place over, which indicates that coastal erosion still has an effect despite all efforts to mitigate it. If coastal erosion was not occurring at all, then the data would show a more dramatic rate of increase. It is important to realize, though that not every country in the world has the resources to experiment with prevention methods like Italy does. This means that worldwide, barrier islands are more likely to shrink as Horn Island and Cumberland Island have than they are to maintain their area, especially as sea levels rise. As barrier islands diminish, it is likely that their ability to shield the mainland will too.

To continue the valuable work involved in this study, other scientists should expand upon it by examining other barrier islands across the globe. This study really shows only preliminary results as it explores only three of over 2,000 islands worldwide. As pandemic restrictions ease, it would also be beneficial to implement a field component to the study as was originally the plan for this project. This way, firsthand information about the environments in which these islands are located can be documented. Frequent visits to these locations would give scientists updated information on how the coastlines of these areas are changing, as this is not always the case with Google Earth.

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