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Should mangrove forests be used as coastal protection for the Gulf of Mexico from future climate effects: A look at the Houston Galveston area.

Benjamin L. Weldon
University of San Francisco, blweldon@usfca.edu

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This Master's Project

Should mangrove forests be used as coastal protection for the Gulf of Mexico from future climate effects: A look at the Houston Galveston area.

by

Benjamin Weldon

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Benjamin Weldon Date John Callaway, Ph.D. Date

Abstract

Climate change effects pose a major threat to coastal cities. Sea-level rise and an increase in hurricane intensity will increase the need for protection for these communities. Wetland ecosystems provide key protective services to the cities that lie behind them. Mangroves are a coastal wetland with benefits such as wave attenuation, carbon sequestration, and shoreline management. Mangrove's habitat range will expand northward as climate change progresses. With a 2-4°C increase in winter temperature extremes black mangroves are projected to be able to inhabit the entire coast of the Gulf of Mexico. The viability of using mangrove forests as future protection for the Houston Galveston area was evaluated with the conditions of replacing the native salt marshes entirely with mangroves. The total net cost of the endeavor was calculated by placing monetary prices on each of the 5 identified benefits to give a range of total projected prices. Using spatial analysis four areas in the region were identified as being areas of high ecological value while accounting for costs. When compared to current protection plans for the study area would be economically viable and beneficial to the region. Annual benefits totaling 60 million dollars would benefit the region for as long as the mangroves are present. Utilizing the areas highlighted in the spatial analysis to focus current wetland restoration can provide more effective immediate protection. The tailoring of specific economic models to the region would prove a more dialed in price estimation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Introduction

Climate change is a global environmental threat that will reshape the world over the coming century. Problems presented by climate change affect every corner of the globe, from the shifting ranges of biomes to the acidification of the ocean (Shaftel et al. 2021). While this is a global phenomenon, different regions will experience problems to varying degrees depending on criteria such as latitude, elevation, and proximity to the coast (Jones et al. 2020). Each region will warrant unique and specialized approaches to mitigate the effects. Coastal cities are among those that will be drastically affected by climate change (Van Coppenolle and Temmerman 2020). Being an interface between land and sea these communities will experience climate change from both sides. Sea-level rise (SLR) and altered storm regimes are climate change mechanisms that will be of particular interest to coastal communities (Shaftel et al. 2021).

Sea-level rise will be a large issue for coastal communities as climate change progresses. As the temperatures rise mountain glaciers and ice caps will melt, introducing more water into the oceans and increasing sea level directly. This is also compounded through the thermal expansion of water. As water temperatures increase the density of water decreases, leading to the same quantity of water occupying more volume. Coastal communities will have to find a way to deal with this influx of water or face large monetary damages.

With the rising ocean and air temperatures providing more fuel to intensify hurricanes, it is expected that we will see an increase in the number of major storms (Category 3 or higher). This increase will present a major problem to the Southeastern United States as the National Oceanic Atmospheric Association (NOAA) reports that 85% of the storm experienced in the United States comes from storms categorized as 3, 4, and 5 (Fabiano 2021). Knutson et al. (2015) found through modeling that by the late 21st century North America can expect a 42%

increase in category 4 and 5 hurricanes due to the effects of climate change. Bhatia et al. (2018) anticipates that category 5 storms alone will increase in frequency 135.5% by 2081 in the Atlantic Basin, even insinuating that the current categorical system be altered to encompass the higher projected wind velocities. These larger more intense storms are also associated with higher rainfall, higher wind velocity and larger storm surges (Bhatia et al. 2018).These trends for storms to have an increased capacity to inflict damage will force coastal cities to assess the potential damages should a direct hit occur and highlight the need to implement defenses to mitigate them.

Rising temperatures around the globe also will allow tropical species to increase their ranges into more northern reaches, while colder adapted species will see their ranges drastically reduced. This trend opens up ecosystems and communities along the biome boundaries to disturbances by foreign species. Non-native species commonly pose a danger to the host ecosystem by providing competition to the native species. This introduced competition displaces populations and creates fragmentation in previously healthy ecosystems (Hengeveld 1988). Non-native species can be costly to communities by diminishing the benefits that surrounding ecosystems provide. The physical act of removal can be extremely costly as well and is infrequently successful outside of island communities (Angeler and Alvarez-Cobelas 2005). The establishment of one non-native species can open the door for additional species to invade and become established further incurring cost on the local community (Britton et al. 2019). As these ecosystems are adapting to other aspects of climate change becoming weakened by non-natives can lead to even larger detrimental effects.

Coastal cities benefit economically from their proximity to the ocean but consequently facing a number of climate change associated risks. These communities have always needed protection from biotic and abiotic factors and historically have been addressed with engineering and altering the environment to meet human needs. Since modern cities are incapable of moving inland without exceptional costs they must be creative in their methods of defense. Traditionally hard structures have been used as a form of coastal protection. These come in the form of seawalls, levees, or jetties, among others. While these structures are effective at addressing the problems, they have some severe limitations. Hard engineering structures can be very costly to construct and maintain. Seawalls cost between 2,800 U.S. Dollars (USD) m^{-1} and 6,900 USD m^{-1} (Hudson et al. 2015). Rigid structures lack the ability to adapt to changing conditions presented by climate change. As sea level rises these structures need to be altered to withstand the increased volume or be replicated further inland. Hard structures also come with unexpected consequences to the ecosystems around them (Hanley et al. 2020). They can disrupt sediment supplies and ecological functions by limiting tidal access and have been shown to increase erosion on either terminal of the hard structure. This increase in erosion gives the illusion of the need for more hard structures (NPS 2019). New construction of hard structures is being phased out and even banned in some states across the U.S. due to the numerous downsides (NPS 2019). Techniques of using natural ecosystems as a means of protection is being explored and as a way to soften these hard structures.

Using natural infrastructure as coastal protection is a practice that is being explored more as we turn our eyes towards the future. Natural infrastructure can be much less costly when compared to hard structures (Hudson et al. 2015), but they do require more maintenance and associated costs. Natural infrastructure provides many additional benefits when compared to hard structures. Instead of being a rigid foreign structure, ecosystems offer natural spaces for native species to utilize as they see fit while still offering the protection of hard structures. They can provide suitable areas for breeding and the raising of young. Natural ecosystems also promote biodiversity for both terrestrial and marine species (Hanley et al. 2020) in ways that hard structures cannot. Reefs and seagrasses can be incorporated in a living spine that provides economic benefits in the form of lessening wave energy and flooding while also promoting fisheries and recreational activities (Guannel et al. 2016). Wetlands are a great example of an ecosystem type that is well suited for natural coastal protection. There are a variety of naturally occurring wetlands that have historically provided protection along the coasts but have been lost or drastically reduced in acreage dure to anthropogenic activities.

Restoring wetlands can provide protection and natural functions while being cost effective. Restoration projects concerning mangroves have a wide array of costs depending on many different variables. Size and length of the project are two direct indicators of price as the larger and longer the project the more the expected costs can be (Hudson et al. 2015). The economic standing of a country also determines the costs of the projects, developing countries will have lower labor costs and other necessary purchases will be less costly when compared to developed countries. In a review by Bayraktarov et al. (2016) mangroves were seen to have both the most and least expensive restoration projects; this is due to the difference in project locations. Australia and USA exhibited much higher costs per hectare than Thailand and the Philippines. Another aspect that contributes to cost is the methods used. Simpler methods using shovels and hand tools will be more cost effective than complex systems and advanced machinery. Mangroves planted by hand and monitored in the restoration area will cost less than those that have been cultivated under controlled conditions in a greenhouse. While corners can be cut to ensure lower costs they can also lead to lower success rates among restoration projects. (Lester et al. 2020)

Study Area

The area of study for this paper is the Gulf of Mexico (GoM) coastal U.S region. This region is located in the southeastern U.S. and covers 2700 km spanning across five states (Thorhaug et al. 2019). Fifty-three million people live within 80 km of the GoM with more people moving to the region each year. The GoM is a large economic source for the U.S. being responsible for 108.21 billon USD (adjusted for inflation $75.7 billion in 2003) each year from various industries (Yoskowitz 2009). The area is very productive and rich in resources providing 78% of all the shrimp and nearly 20% of all gas and oil production for the country (NOAA 2008). The region also boasts a large tourism industry of 35 billion USD annually that is based on the recreation activities and aesthetic beauty of the region (Yoskowitz 2009). The GoM is generally a low-lying area that is very susceptible to SLR along with hurricanes that hit the region annually. Given the economic benefits and the climate related problems it faces the GoM is a prime example of where natural ecosystems could be implemented for coastal defense. Currently the majority of protective coastal ecosystems that litter the Gulf are salt marshes.

To investigate how economically viable this endeavor would be, the scale will be reduced even further to the Houston Galveston area (HGA). This area is located on the eastern coast of Texas and will include four counties: Brazoria, Chambers, Galveston, and Harris (Figure 1). The population of these counties is 5,381,497 according the to 2020 U.S. census. This is the largest metropolitan area along the GoM and is of a large economic importance as well. The area is situated around Galveston bay and supports 4 major ports (Houston, Galveston, Freeport, and

Texas City). The Port of Houston is the nation’s busiest waterway in terms of foreign tonnage, second in terms of total tonnage, and home of the largest petrochemical complex in the nation (HGAC 2015, LaRue et al. 2016). The HGA is also the nation’s sixth largest regional GDP and is one of the most rapidly growing in the country (Lingala 2021). Protecting this region would prevent billions in damages and operational losses along with preventing a potentially catastrophic ecological disaster should the petrochemicals be released into the bay.

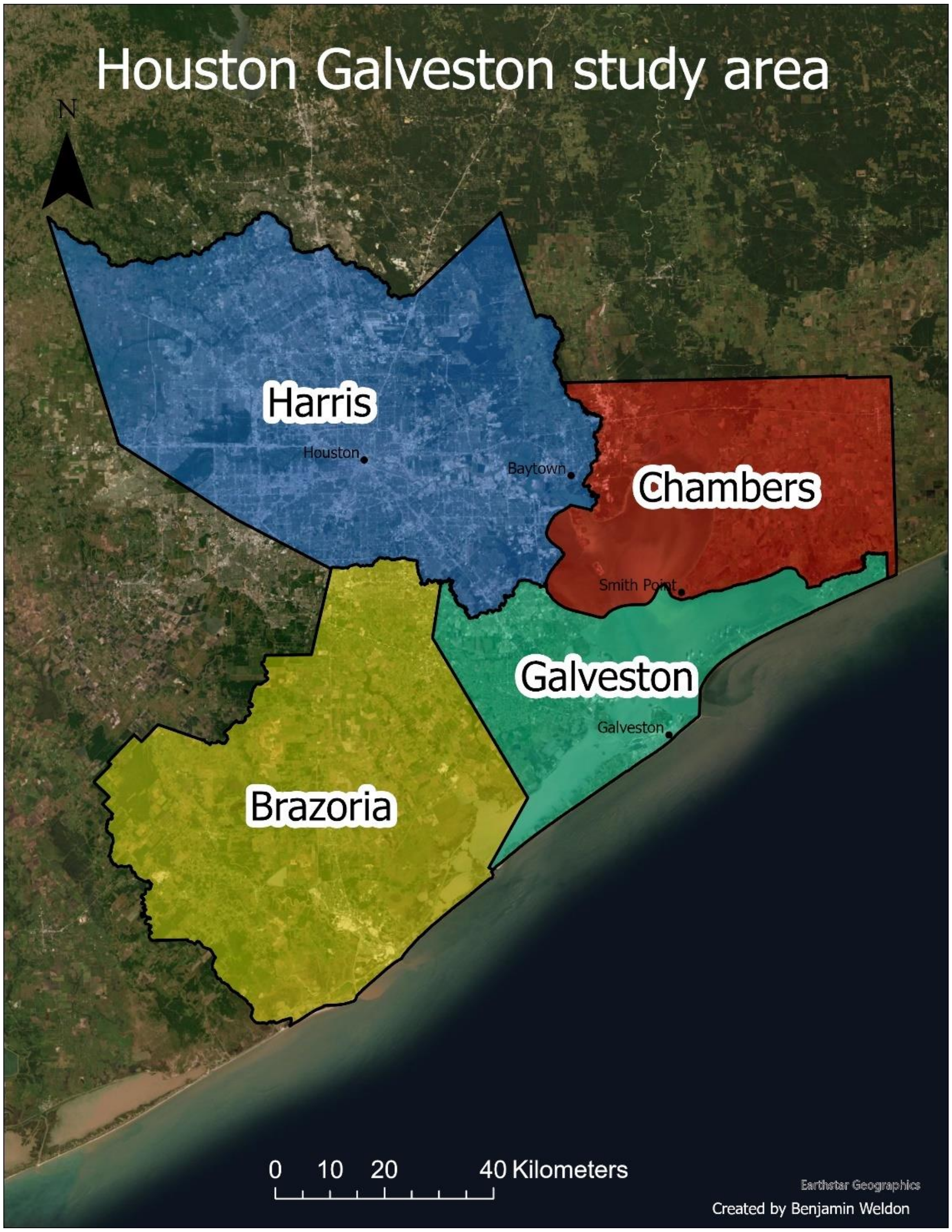


Figure 1: A map of the Houston Galveston area and the four counties examined in this paper.

Houston is a city already prone to floods and disaster, it exhibits one of the slightest slopes in the entire country at less than 0.2 meters per kilometer (Schaper 2017). Downtown Houston is situated 80 km inland from the GoM and is only 15 m above sea level. Certain areas of the city have subsided up to 3 m. Elevation in the region lessens as you approach the coast with the city of Galveston being only 2 m above sea level. Since 1983 the Federal Emergency Management Agency (FEMA) declared 26 natural disasters in the greater Houston area (UH.org 2021). Floods make up 12 of these events and hurricanes and tropical storms make up 10 events (5 events each). As more and more people move to the area they continually expand onto the flood plains exposing more and more of the population to flooding. At the start of 2021 over 322 thousand residential properties (21.7% of total) are located in a FEMA designated floodplain and that number is expected to increase by 2050 (UH.org 2021). When you examine the location of reported damages, it shows that even more of the population is at risk. Insurance claims in Harris county between 1999 and 2009 shows that 75% reside outside the 100-year flood plain while none of the 5 events that occurred during that time frame qualified as a 100-year storm (UH.org 2021). Additionally, 55% of damages resulting from the 2016 Tax Day Flood resided outside the 500-year zone. This shows that even homes outside of the marked flood plains are still at a risk to experience flooding.

Houston Galveston area has seen tremendous monetary losses in recent years from hurricanes: 125 billion USD from Hurricane Harvey in 2017, 28 billion USD from Hurricane Ike in 2008 and 5 Billion USD from tropical storm Allison in 2001 (Amadeo and Estevez 2020, HCFCD 2021). However, this is not a recent issue the “Great Galveston Storm” devastated the region in 1900 causing 40-50 million USD in damages and taking the lives of 6,000-8,000 people leveling the city. Floods also have a long history of destruction in the area. The “Memorial Day Flood” in 2015 created 459.8 million USD in damages and the two flood events in April 2016 estimated 1.9 billion USD in damages. From May 25, 2015 to October 31, 2018 the area experienced eight major flooding events. As seas rise and storms intensify dropping even more precipitation on this flat region even more flooding and losses are to be expected.

Research Questions

This paper will investigate if mangrove forests should be considered to replace the natural salt marshes as climate change will expand mangroves range to the entire region. Seagrasses are not being included in this analysis since they can coexist with mangroves and salt marshes provide added benefits to both ecosystems (Guannel et al. 2016). This paper will examine the consequences both intended and unintended of introducing mangroves to the HGA. Each identified consequence will be monetized and totaled to provide an estimated range of how much it would cost to create mangrove forests all along the bay and Galveston island. Since replacing the majority of the coastal salt marshes with mangroves is not economically viable a spatial analysis will be done to pinpoint the areas that would benefit the most from implementation while factoring in costs. At the conclusion of this paper, you will have been presented with a comprehensive comparison of mangroves and salt marshes within the context of coastal protection services regarding climate change. You will see how economically viable this endeavor would be and you will be presented with a map that highlights which parts of the HGA would benefit the most from the presence of mangroves while factoring in costs. Answering the questions of:

1. What are the comparative benefits of mangroves vs salt marsh?
2. How economically viable is the implementation of mangroves in the Houston Galveston area?
3. Which regions of the study area would benefit the most from mangrove protection?

Methods

The methods utilized in this paper include the incorporation of relevant literature, economic assessment, and the use of Geographic Information Systems (GIS). The literature was collected from multiple research databases including but not limited to Scopus, ResearchGate, and JSTOR. The papers were then synthesized, and the information was used to comprise the majority of the comparison segment of this paper and also to bolster the economic analysis and GIS work. Literature on both salt marsh and mangrove ecosystems and the way they interact with each identified consequence were examined. This provided insight on the strengths and weaknesses of each ecosystem type in regard to climate effects. A comparison between the two was then able to be made as a justification to consider the implementation of mangroves a non-native species to the HGA.

The economic assessment was done in accordance with the Environmental Protection Agency's (EPA) published document entitled "A framework for the economic assessment of ecological benefits" (EPA 2002). A flow chart was created (Figure 2) to illustrate the main action and the consequences from that action. The main action is in the black rectangle, consequences are in the blue ovals, and ecological endpoints are in the red circles. The green squares represent the economic endpoints that are monetized. The consequences that were chosen for this paper are some of the most common ecosystem services associated with wetlands and with climate change. Other consequences that were left out would be more appropriately incorporated in further analysis. The same approach was taken with the ecological endpoints. Due to the scope and limitations of this examination all of the endpoints are higher level with many other aspects that could be examined in other papers. An example of this is that this paper stops at reduced shoreline erosion while in fact it can be broken down further into improved recreation and water quality that can be separately monetized. The economic endpoints are the largest high dollar outcomes from this main action and were chosen to represent costs most accurately with the limited number of variables.

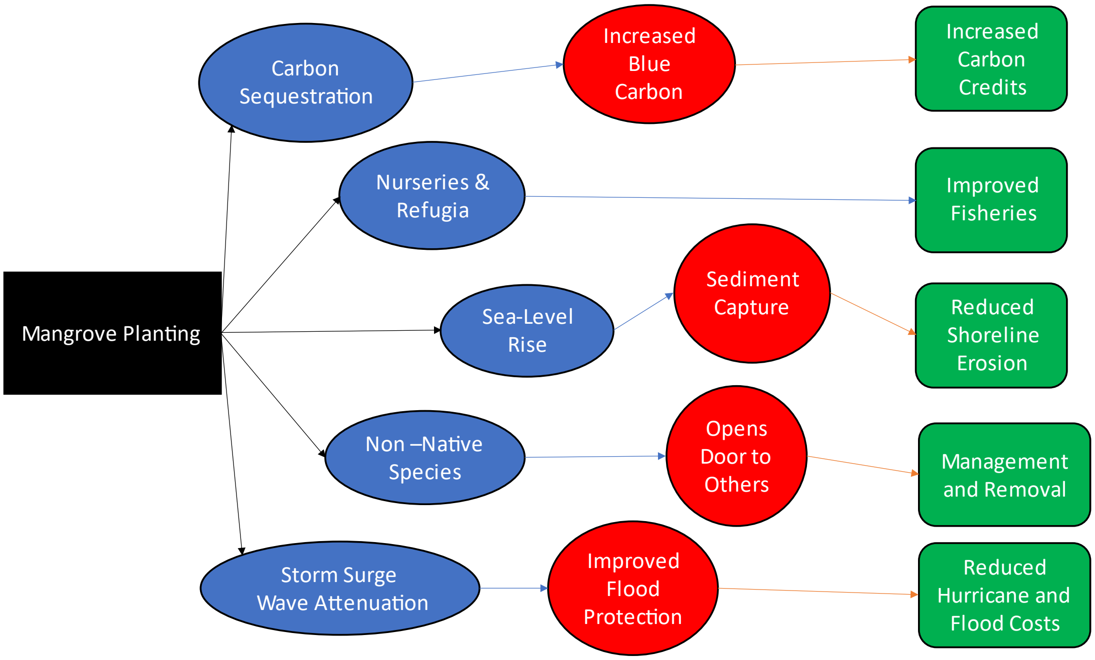


Figure 2: Flow chart of the main action (black) and the associated benefits (blue). Consequences (Red) and then the monetary endpoints are in the green.

The monetizing techniques utilized in this paper are mostly comprised of benefit transfers taken from various papers reflecting areas most like the study area (EPA 2002). Prices for relevant services were determined from the literature (Table 1). The prices were used for each economic endpoint in the way most appropriate to the proposed plan and which would produce the most accurate results given the study area data. The individual costs were compiled to provide an estimated total cost of the project for the full 15 years. As these benefit transfers are catered to comparable areas and not the exact study area, varying prices were used to provide an estimated range rather than an exact price to avoid assumptions that this is a fully comprehensive economic evaluation.

Table 1: List of services and the prices that were used in this paper. the sources of these numbers are included

Service	**Price**	**Frequency**	**Source**
Implementation cost (Low)	48,000 USD ha^{-1}	Once	Bayraktarov et al. 2016
Implementation cost (Medium)	132,000 USD ha^{-1}	Once	Bayraktarov et al. 2016
Implementation cost (High)	525,000 USD ha^{-1}	Once	Bayraktarov et al. 2016
Carbon Sequestration	20 USD ton^{-1}	Once	Deign 2020
Nursuries and Refugia (Marsh)	36,000 USD fringe ha^{-1}	Annually	Frederick Bell 1997
Nursuries and Refugia (Mangrove)	48,000 USD fringe ha^{-1}	Annually	Oropeza et al. 2007
Nursuries and Refugia (Difference)	12,000 USD fringe ha^{-1}	Annually	Difference between two
Storm Surge (Wetlands)	2,300 $ha^{-1}yr^{-1}$	Annually	Siverd et al. 2020
Storm Surge (Mangroves)	4,000 $ha^{-1}yr^{-1}$	Annually	Narayan et al. 2019

A fuzzy logic map was created to best assess which regions of the study area would be both of highest ecological value while mitigating costs (Hattab et al. 2013). Fuzzy logic maps have been used and proven to be effective at predicting habitats due to the ability to deal with the uncertainties that organisms often provide (Hattab et al. 2013). Fuzzy logic was chosen as the analysis method in this project since it was able to provide a range of the most and least suitable sites for mangrove plantation for the entire study area. The first data set utilized was a land use classification, provided by the Houston Galveston Area Council, that broke the region down into 10 different land use classifications. The land use classifications were reclassified using the reclassify analysis tool with values of 1-11. These were based on the cost needed to convert to mangroves with 1 being the costliest and 10 being the cheapest (11th is no data for the middle of the GoM). The factors used to determine cost of alteration were existing structures (Highly developed is more costly than low developed) and the potential economic earnings (Agriculture is more costly than shrub or forest). This newly reclassified layer was assigned a linear fuzzy membership with a minimum of 1 and a maximum of 11.

The other layers were provided by NOAA and are SLR layers for the study area of 1m, 2m, and 3m and illustrates the regions that would be inundated under each condition. These layers were made by NOAA taking into consideration the elevation, topography, and tidal actions of the area. These three layers were then merged together to create one layer using the merge tool. The three individual layers can be identified by the shape area field on the new layer table. As this is a vector layer it needed to be converted to a raster using the analysis tool “convert to raster”. The two fuzzy maps were then combined using the fuzzy overlay tool and using the “And” overlay type. This final map shows the areas of the HGA that would benefit the most from mangrove protection while being the most cost effective.

Comparison of mangroves and salt marsh ecosystems

Mangrove Overview

Mangrove forests are dominated by woody vegetation in tropical and subtropic regions of the world. They are commonly found in inter-tidal saltwater areas and are biologically complex ecosystems. Ranges are determined by low winter temperatures which inhibits expansion northward, as mangrove species do not fare well with freezing events. There are 54 true species of mangroves (approximately 70 classified) which are trees and shrubs that are adapted to living in saline low oxygen environments that deal with frequent inundation. Many species have developed unique adaptions to dealing with the harsh environment. Some of the most common are the use of arial roots and pneumatophores to allow oxygen intake. Mangroves can grow from a few meters high to up to 45 meters tall. This variability in size and shape causes forests to have vastly different shapes and structures based on the physical location along the coast and assemblage of different species within. Some mimic inland forests with developed canopies and understories while others will exhibit simpler structures. Beneficial functions of mangroves that will not be touched upon later are they act as nurseries and refugia for many diverse species, they provide timber, and act as a water filtration system.

For the purpose of this paper the GoM region will be highlighted. Three native species of mangroves dominate this region: Red Mangrove (*Rhizophora mangle*) a species that is usually found in standing water that can reach heights of 22 m, Black Mangrove (*Avicennia germinans*) a species (12-18 m) that can grow more inland than red mangroves and excretes salts through leaves, and White Mangrove (*Laguncularia racemosa*) generally smaller and typically found more shoreward than the other two species. These three species are found in mosaic distributions along the Gulf Coast but mainly Florida. As climate changes they will be afforded more range northward as winter deep freezes are projected to be less frequent. It was seen that an increase of only 2 to 4°C of winter extreme temperatires will allow black mangroves to grove comfortably all around the GoM (Osland et al. 2020). Black Mangroves are the most cold tolerant species of the three. Osland et al. (2020) found that black mangroves sustain leaf damage around -4°C and have a risk of mortality around -6.6°C (90% and 45% biomass regrowth at both temperatures). If projections of climate change are accurate large mangrove forests could be sustained year-round around the entire GoM and supplant the salt marsh which currently dominates.

Salt Marsh Overview

Salt marshes are primarily dominated by herbaceous vegetation. They can be found all over the world from tropic to temperate climates in inter-tidal saltwater areas. Like mangroves they are a very biologically complex system that most of the vegetation biodiversity comes from a few families. They are mainly comprised of pickleweed (*Salicornia* spp.) and cordgrass (*Spartina* spp.) both genera are found worldwide. As a wetland they are held to the constraint of being an anoxic saline environment that deals with daily tidal flooding, not many species of plants are equipped to handle these parameters. While cordgrass species can grow to great heights (2-3m) and provide canopy cover e.g. *Spartina alterniflora*, salt marshes usually contain little to no tree canopy cover. Much like mangroves salt marshes also act as sources of water filtration, nurseries and refugia for numerous species. Unlike mangroves salt marsh vegetation can handle extreme cold and freezing events which leads to its worldwide distribution (Osland et al. 2020). In the GoM salt marshes are the dominant coastal wetland and cover most of the coastline (Thorhaug et al. 2019). With current climate projections salt marshes on the Gulf Coast face a number of threats. Among them is the possible encroachment of mangroves, that tend to outcompete the marshes in tropical environments where both occur naturally (Dontis et al. 2020).

Wave attenuation and storm surge

Mangrove forests and salt marshes play a pivotal role in normal wave attenuation and the slowing of storm surges. Mangroves lessen the energy of waves because the vegetation creates drag, as the wave enters and progresses through the forest it experiences drag. This reduces the wave speed continually the farther it penetrates the forest. Higher rates of attenuation are correlated with denser vegetation. Horstman et al. (2014) observed wave attenuation rates among mangroves were significantly higher than what has been seen on neighboring mudflats with little to no vegetation. Mangroves are also quite effective at attenuating storm surges from hurricanes. The higher volumes of water are affected much in the same way as normal wave action, primarily through vegetation drag. As the large surge of water begins to contact the mangroves the water slows and rises even higher than seen in open water, much like cars on a highway reaching a merge. As the slower water passes through the mangroves it results in smaller surges on the shoreward side, this can be seen in Figure 3 (Birch 2020). Even if the whole forest becomes submerged it can still have lessening effects on the surge depending on the depth that of inundation and the amount of vegetative biomass the water moves over (Birch 2020). The degree to which mangroves affect storm surges are related to the speed at which the storm approaches; the faster moving the storm the more effective the forest will be at dissipating the energy and slowing the water (Zhang et al. 2020). In simulations using 6-10 meter tall trees hurricane surge heights were decreased by 60% (Krauss and Osland 2020) The actual efficacy depends on the coastal characteristics, such as elevation, physical shape of the coastline, the forest’s location long it, and storm intensity. These simulations give a scale as to what can be expected under ideal conditions.

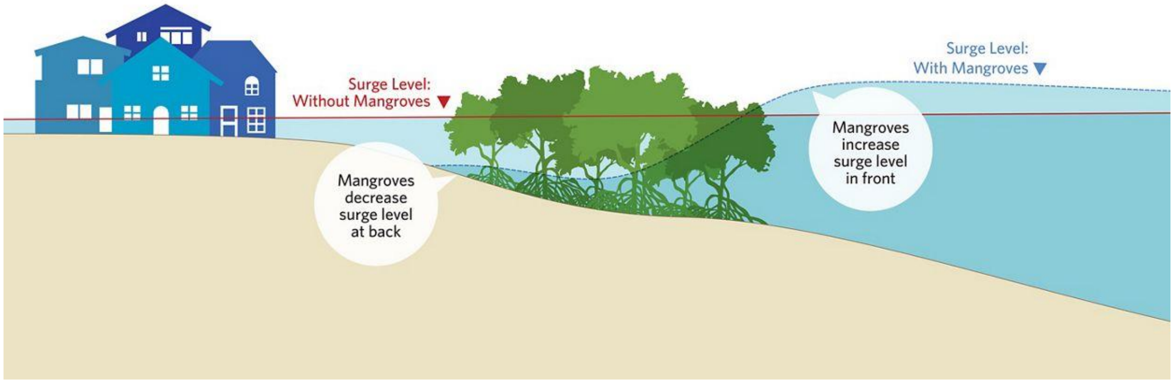


Figure 3: Physical depiction of the mangrove storm surge attenuation. (Birch 2020)

Salt marshes mitigate storm surges and normal waves in much of the same way as mangrove do through vegetation drag. As the water passes through and over the marsh the wave energy is lessened the same way as in the mangroves. Since the marshes are smaller in height compared to the forests they are less effective against high storm surges that pass over top. They still lessen the effects but not as efficiently. Salt marsh are much more effective at lessening normal wave action than storm surges.

Hurricane impacts and injuries

Tropical cyclones such as hurricanes are a major source of disturbance for mangroves and salt marshes in the southern United States. The more effectively these systems are able to mitigate the effects of the storms the more protection they can provide to human infrastructure and other inland ecosystems. As coastal ecosystems, they are the first to encounter these large storms and bear the brunt of their force. Mangrove’s primary threat from hurricanes is wind velocity damage to individuals through a complete breakage of the stem or being blown over and uprooting. Similarly to storm surge, mangroves can also decrease the hurricane’s wind velocity

(Das and Crépin 2013) this was seen to have lessening impacts on structural damage to villages 20-30 km away from the mangroves compared to villages without mangroves in the storm's path. The tallest of the trees in the forest are the most likely victims of velocity damage as they catch the wind the easiest. As the storm surge passes through the smaller trees are submerged and are then protected from the wind, a benefit the largest individuals do not share. While all trees might not experience mortal injuries, they still experience the loss of leaves and small limb breakages, severity depends on the intensity of the storm. A years' worth of leaf litter and woody debris can be accrued during a single storm event (Krauss and Osland 2020).

Delayed mortality has been observed in mangroves up to a year after the initial storm event. This can happen from trees being uprooted or having structural damage to the roots or stems. Infrequent reasons for delayed mortality are sedimentation by hurricanes dams the water and creates an anoxic environment above the root line or can simply smother the roots preventing respiration (Radabaugh et al. 2020). A total collapse of the mangrove peat resulting in a complete loss of the ecosystem can also be a consequence. This phenomenon was seen in 1935 in Cape Sable, Florida after the most intense hurricane to ever make U.S. landfall. The forest mortality and collapse of peat caused the area to become devoid of mangroves and was transformed into mudflats (Krauss and Osland 2020). While a category 5 hurricane guarantees a collapse of the mangrove peat it does not always lead to a complete loss of habitat.

Fragmentation of mangrove ecosystems make the forests more susceptible to elevated levels of destruction from hurricanes and even increases the likelihood of damage to human settlements behind the mangroves (Krauss and Osland 2020, Das and Crépin 2013). Like mangroves salt marshes also are at higher risk of destruction when fragmented due to limited functionality (Hanley et al. 2020). Armitage et al. (2020) studied experimental plots of both salt marsh and mangroves that were in the direct path of Hurricane Harvey a category 4 storm. They found that mangroves lost 25-40% canopy cover due to large trees being snapped or blown over as they stood above the storm surge water levels, marsh vegetation was largely unaffected due to complete submersion. Additional findings were that mangrove plots were very resistant to erosion (< 0.5 m) where marshes had substantial loss (> 5 m) but only gained half as much storm deposited soil when compared to the marsh.

As primarily herbaceous communities hurricanes affect salt marsh differently than seen in the mangroves. The risk of vegetation breakages is dependent on the species and the flexibility of the stalk, breaks are still a much lower risk than in mangroves as the entire marsh becomes submerged beneath the surge of water. High velocity winds and strong currents can dislodge the root mats and compress them into ridges much like the squeezing of an accordion (Cahoon, D. R. 2006). This removal of root mats can cause significant elevation changes raising areas on the top of the ridges potentially 2 m and lowering where they used to reside flat. As seen in the Armitage et al. (2020) study during hurricanes salt marshes experience drastic erosion to the marsh seafront but also receive a tremendous amount of sediment as well. A single storm event can dump the equivalent of over a century’s worth of sediment that would accrete under normal conditions (Hanley et al. 2020). This massive amount of material can smother the native plants causing mortality and reduce seedling establishment. While not much debris is generated from the marsh itself foreign debris can be transplanted by the storm causing adverse effects to the vegetation and environmental factors.

Ability to recover from hurricanes

Tropical cyclones can be an annual event in the GoM and the ability for ecosystems to recover quickly and effectively can affect the resiliency against future storms (Reja et al. 2017) Frequent disturbances from hurricanes cause many recovery problems for both mangroves and salt marshes. Mangroves face a number of challenges immediately following a major storm event. Delayed mortality is an issue for forests and the openings in the canopy from injured trees and the loss of leaves create new abiotic conditions that cause stress to surrounding trees. Saplings and understory individuals will face increased direct sunlight causing an increase in growth and metabolism. Without shade the mangroves would also experience higher air and soil temperatures which increases the need for water efficacy (Krauss and Osland 2020).

There are two main types of recovery utilized by mangroves. Advance regeneration where the seedlings are already established before the disruption and can quickly grow after the event, capitalizing on the now available resources e.g. light and space. The second method is that some species of mangrove can sprout rather rapidly from broken limbs, stems, or lateral branches. These strategies allow the forest to replenish its canopy substantially in a short amount of time. Radabaugh et al. (2020) found that in the Ten Thousand Island area of Florida following Hurricane Irma (September 2017) it only took 3-6 months to return to 60% canopy coverage where it was below 40% 1-2 months following the storm. This sort of rapid growth works to quickly reestablish pre-storm abiotic factors and can relieve some of the stress introduced during the disturbance. Propagule creation in mangroves and hurricane season have similar timing, this could be an evolutionary adaptation to utilize the storms in mangrove recovery. The storm surge and strong winds have the potential to carry the propagules farther than the average tidal action.

This can help with replacing the trees damaged in the storm and can also deposit seeds inland for potential future use (Krauss and Osland 2020).

Hurricanes also act as a way to fertilize the forests and replenish nutrients through sediment deposits from the storm surge. Castaneda-Moya et al. (2020) investigated this phenomenon after Hurricane Irma. They reported findings that the mangrove rich southwest estuaries of Florida, that were directly hit, had five times the amount of total phosphorus loading rates as opposed to the southeastern side. While sediments deposited by the storm surge provide instant nutrients for recovery, the leaf litter and especially the woody debris act as a time delayed source of nutrients for the forest as it takes longer for decomposition (Krauss and Osland 2020).

Salt marsh recovery can be rapid depending on the amount of disruption. Any elevation changes introduced by the storm opens up the opportunity for colonization, allowing the marsh to extend outward. The folding of the root mats described by Cahoon (2006) can create substantial pockets of elevation change by stacking the torn mats on the original root mat creating new areas that are bare. Early colonizers could disrupt the species richness of the marsh by excluding other species that persisted before the storm event and were subsequently displaced. The nutrients deposited by the storm could change the biogeochemistry of the soils by changing the redox potentials and increasing the rate of decomposition in the marsh directly following the storm event (Hanley et al. 2020).

Sea-level rise

Sea-level rise is a huge consequence of climate change that poses a grave threat to mangroves and salt marshes. The way they accommodate it is vertical climbing through sedimentation and erosion mitigation. As the earth's climate increases, SLR is caused by a few drivers. The oceans are projected to rise at least 0.6 m by the year 2100 (McKee, K. L. 2011). This effect will not be felt uniformly all over the globe, low lying areas with minimal slopes (e.g. GoM, islands, and parts of southeast Asia) will be greatly impacted and coastal wetlands are on the forefront as intersections between marine and terrestrial biomes . For these coastal ecosystems to persist in the future they will need to accumulate sediment at a rate close to or above SLR rate (Cahoon, D. R. et al. 2020). As they continue to build vertically they must also be able to control the amount of lateral erosion by normal wave action and storms.

Mangroves and marshes mitigate erosion by the presence of vegetation, the roots help to stabilize the soil, so it is not so easily compacted or washed away. The vegetation also aids in the sedimentation process by slowing the water that passes through it allowing the sediment being carried to fall out of suspension and settle in the wetland. The roots can also act as sediment traps much in the same way an air filter traps particles as the air passes through it. In salt marshes, as this sediment is trapped on the seaward side it allows the plants to settle on the newly accreted soils and extend the wetland (Hanley et al. 2020). Organic material that settles on or below the surface is also a large part of vertical expansion. In some mangroves that are not flushed regularly leaf litter can account for accumulation rates of 1.1 to 3.4 mm year^{-1} (McKee, K. L. 2011). As salt marshes do not produce much leaf litter they increase their organic material in the soil by the presence of root mats, deceased vegetation and trapping of foreign debris. As they are both wetlands, and characteristically experience anoxic soil conditions, decomposition is slow and organic matter can be collected in the form of peat. This peat can be quite thick (> 5 m) in both ecosystems and plays a large role in the carbon sequestration services that each wetland provides.

If vertical expansion is not fast enough to keep up with SLR then the alternative for mangroves and marshes is to migrate shoreward to higher elevations to avoid drowning. If SLR is too quick for the mangrove to accommodate then they will be lost, and a tidal mudflat would be formed (Cahoon et al. 2020). This can be an issue in many places due to the establishment of human infrastructure. This coastal squeeze can doom wetlands by blocking them from inward expansion, the system will become inundated and drown and the coastal city will no longer benefit from any of the ecosystem services that previously protected it.

Coastal wetlands in the GoM can get the supplemental boosts of vast amounts of sediment being deposited during hurricane events. This extra input can help wetlands stay ahead of SLR but cannot be relied on as the sole source of sediment (Feher et al. 2020). Hurricanes are unpredictable in path and frequency; the same wetland may be affected in consecutive years then wait decades before the next event. Mangroves sustain more structural damage and mitigate erosion better on average from hurricanes than salt marshes do. The salt marshes studied along the northern Texas coasts tended to receive more sediment from hurricanes during the observation periods (Armitage et al. 2020). This could be a result of the limitations black mangroves currently face in the area due to thermal constraints. Fully functional forests might not exhibit such a disparity.

Carbon sequestration

Mangroves and saltmarshes are both highly effective at capturing and storing blue carbon in large quantities. Blue carbon is carbon that is stored in underwater ecosystems such as coastal wetlands. The ability for coastal wetlands to sequester carbon is vitally important to their survival, as the more carbon that can be removed from the atmosphere the more mitigation from the effects of climate change. As these coastal ecosystems are lost through climate change or anthropogenic effects the carbon they have stored will be released and could drive climate change further resulting in a positive feedback loop. Mangroves and salt marshes are able to sequester a large amount of carbon as they grow. Once the individuals die the carbon in the organism and the surrounding litter are transformed into peat, that carbon is sequestered in the substrate due to the low decomposition rates (Kida and Fujitake 2020).

The GoM is home to many mangrove and salt marsh communities that sequester an extreme amount of carbon. According to a blue carbon stock study of the GoM conducted by Thorhaug et al. (2019) there are 255,151 ha of mangroves and 497,637 ha of salt marshes on the U.S. Gulf Coasts. The spatial distribution of this is extremely lopsided with only 4,897 ha (1.92%) of mangroves occurring outside the state of Florida. While 217,510 ha (43.71%) of salt marshes reside in the same area. This distribution is caused by the tropic climate of South Florida and the harsher winters on the Northern Gulf Coast that historically have inhibited mangrove populations. Despite only having 51.27% land coverage compared to salt marshes mangroves have sequestered 4.06% less total carbon than salt marshes (102.6 Tg vs 98.43 Tg). This shows that per hectare mangroves are able to sequester more blue carbon than salt marshes in the GoM (0.21 Gg per ha^{-1} vs 0.39 Gg per ha^{-1}). Some reasons for this might be that the warmer temperatures allow for a longer growing season for the mangroves that are predominantly in southern Florida than the salt marshes who reside in mostly cooler climates along the northern coasts (Thorhaug et al. 2019). Another constraint to this study is that Thorhaug et al. (2019) only accounted for carbon that was sequestered up to the first meter in depth. As the peat in some of these ecosystems can be meters thick this could be an underrepresentation of the total amount of blue carbon in the GoM for both ecosystems.

It is unclear what the relative capacity of the two ecosystems is to sequester carbon in the GoM as their data in the same area did not allow for a large enough sample size to compare. Though this increase in carbon stock as landscapes transition to mangroves is well documented. Doughty et al. (2016) measured a 22% increase in total carbon stock during a 7-year period as mangroves became the dominate wetland in a wildlife refuge on the eastern coast of Florida. This was more than double the historical stock rate for the area. Alongi (2015) found the mangroves were able to store about twice as much carbon as was found in the salt marsh. Alongi (2015) also found that salt marsh is able to sequester slightly more carbon per year when compared to mangroves. The ability to capture and store vast amounts of carbon is one of the most crucial benefits that these two systems provide and will be a monumental factor in planning for coastal protection and preservation in the future.

Competition among mangroves and salt marsh

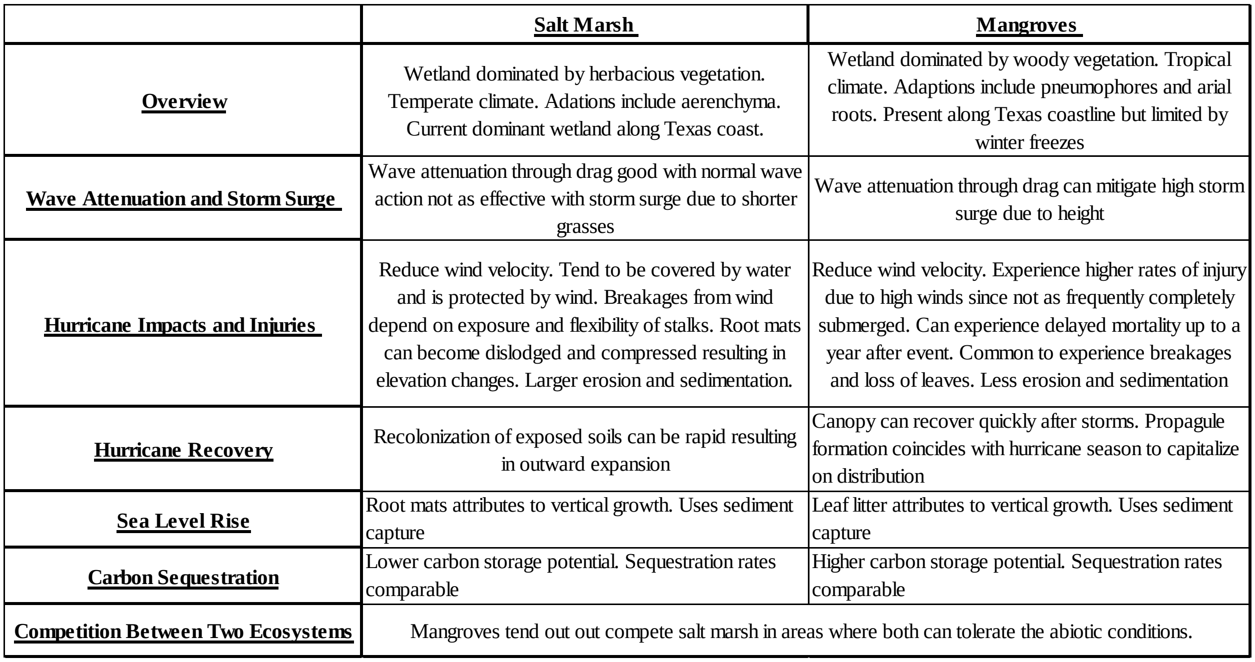
Mangroves and salt marsh ecosystems currently do not overlap extensively in the GoM but when they do mangroves out compete the salt marshes. This has been seen throughout Florida since the 1800’s. Historically encroachment of mangroves northward has been stymied by harsh freezes that kill off the trees and allow the salt marshes to persist. Dontis et al. (2020) describes the transitional effects as such. Mangroves are introduced to established salt marshes through the propagules becoming trapped among the *Spartina spp.* and take root among the grasses. The cover that the grasses provide can insulate the seedlings encouraging settlement but can also be detrimental by blocking light needed for growth. Once they take hold it becomes a transitional wetland where the grass is present along with small shrub like mangroves. As the mangroves increase in size they establish a canopy and in turn prevent the marsh vegetation from photosynthesizing and dying off. As more marsh grasses die off it provides more opportunity for mangrove recruitment (Dontis et al. 2020). This sequence of events was observed over a 26-year period in Tampa Bay, Florida as winter freezes were less frequent and intense. This type of mangrove transition using shading has been studied by Stevens et al. (2006). Salt marsh has already been described as having the limiting factor of their southern ranges in the northern hemisphere being competition with mangroves (Kangas and Lugo 1990). With climate change projections this cycle can be expected to expand northward as minimum winter temperatures increase as this is mangroves limiting factor (Osland et al. 2013).

In models conducted by Osland et al. (2013) a 2° to 4°C increase in mean annual minimum temperature could open the door for 100% of Texas and 95% of Louisiana salt marshes to be naturally converted to mangrove forests. The widespread disturbance to the salt marshes around the GoM could put coastal cities and ecosystems at elevated risk during the transition period as both systems are less resilient as an ecotone when compared to homogeneous regions (Osland et al. 2020). As the mangroves invade the established salt marsh ecosystems it will create fragmentation in both systems diminishing the functionality of each. With less effective means to deal with hurricanes and SLR at a time when the effects are already being observed at a large scale this could potentially be disastrous for the gulf coast

Comparison summary

Each ecosystem has its own strengths and techniques to deal with climate change due to the evolutionary adaptions of the species that dominate the landscape (Table 2). Both are highly productive ecosystems and are among the highest producing ecosystem types. The defining characteristic in their global distributions is temperature restrictions for mangroves are not a freeze tolerant species and the presence of mangroves for the salt marsh (Kangas and Lugo 1990). Freezing temperatures cause mortality events in mangroves which trims them back as they continually encroach into salt marsh ecosystems. Mangroves are more effective at dealing with storm surges than salt marsh are. While mangroves have a higher total carbon storage potential, salt marsh have higher annual rates of carbon sequestration. When these two ecosystems do overlap there tends to be a natural transition to mangrove forests due to the mangrove competitive advantages. While both of these ecosystems provide many of the same benefits the effectiveness of these benefits is determined by the physical characteristics and the way that each functions.

Table 2: Summary chart highlighting the characteristics of both mangrove and salt marsh ecosystems.



	Salt Marsh	**Mangroves**
Overview	Wetland dominated by herbacious vegetation. Temperate climate. Adations include aerenchyma. Current dominant wetland along Texas coast.	Wetland dominated by woody vegetation. Tropical climate. Adaptions include pneumophores and arial roots. Present along Texas coastline but limited by winter freezes
Wave Attenuation and Storm Surge	Wave attenuation through drag good with normal wave action not as effective with storm surge due to shorter grasses	Wave attenuation through drag can mitigate high storm surge due to height
Hurricane Impacts and Injuries	Reduce wind velocity. Tend to be covered by water and is protected by wind. Breakages from wind depend on exposure and flexibility of stalks. Root mats can become dislodged and compressed resulting in elevation changes. Larger erosion and sedimentation.	Reduce wind velocity. Experience higher rates of injury due to high winds since not as frequently completely submerged. Can experience delayed mortality up to a year after event. Common to experience breakages and loss of leaves. Less erosion and sedimentation
Hurricane Recovery	Recolonization of exposed soils can be rapid resulting in outward expansion	Canopy can recover quickly after storms. Propagule formation coincides with hurricane season to capitalize on distribution
Sea Level Rise	Root mats attributes to vertical growth. Uses sediment capture	Leaf litter attributes to vertical growth. Uses sediment capture
Carbon Sequestration	Lower carbon storage potential. Sequestration rates comparable	Higher carbon storage potential. Sequestration rates comparable
Competition Between Two Ecosystems	Mangroves tend out out compete salt marsh in areas where both can tolerate the abiotic conditions.	

Economic viability of mangrove use in Houston Galveston Area

The HGA is a very economically productive area producing 503 billion USD in 2015 ranked 6th among peer regions and continues to be one of the fastest growing economies in the country (HGAC 2015). A lot of this commerce is at an elevated risk of being damaged by hurricanes as it is conducted on or near Galveston Bay and the GoM. The HGA is home to four major ports that account for 315.08 billion USD annually (LaRue et al. 2016). Houston is a global leader in petrochemical manufacturing and makes up 42% of the U.S. petrochemical capacity (Bridges 2019). The protection of these facilities can save the region billions of USD in losses and prevent an ecological disaster should the petrochemical complex become compromised and spill into the bay. So how much in net assets could mangrove protection of the

HGA generate? To answer this question, the EPA's framework was used to make a flow chart that shows the intended and some unintended consequences of the main action (mangrove implementation) and the monetary costs of benefits associated with each (Figure 1). The five identified intended consequences are: carbon sequestration, nurseries and refugia, shoreline management, non-native species, and storm surge / wave attenuation. The non-native species consequence is the only one that was found to not provide monetary benefits and would result in a net cost to the region. The analysis used the wetland acreage data in the HGA (provided by NOAA) and examined converting all of the estuarine wetlands in the study area to mangroves (66,171 hectares in total). The method of alteration is a monitored facilitated invasion of mangroves using both the planting of small tree and propagules with protection.

Cost of mangrove implementation

The implementation of Black Mangroves into the HGA will be a large undertaking with many moving parts. The proposed plan will span over 15 years and be incremental in the conversion to mangroves. The two main methods of planting will be the use of propagules and planting of small adolescent trees. Propagules will be acquired by manual collection from other sites or importation from nurseries and other seed banks. Black mangrove propagules need to be in the water for a period of at least 14 days to be viable (Alleman and Hester 2011). All of the propagules will be held in conditions that mimic the natural temperature and salinity of the study area until roots have begun growing and can be planted to prevent decay. Half will be planted in a nursery under controlled condition to ensure survival to an adolescent stage, the other half will be taken to the study area and planted in previously scouted target areas. Varying elevations and positions within the tides will be documented and the survival results will be documented to fine tune subsequent years for more successful planting. Once nursery trees are large enough to ensure higher rates of survival (1m or taller) they will be transferred to the study area and planted along the same area (Vanderklift et al. 2020) to account for propagules who were not viable.

When the trees in the study area reach sexual maturity, those propagules will be collected manually, and the process will begin again. Outside propagules will still be brought in to ensure genetic diversity but not in as large numbers as the first few years. Alleman and Hester (2011) noticed a trend among black mangroves in Louisiana that there is a cycle among stands where one year more energy is spent on vegetative growth and little energy is put into reproduction, the following year there is little growth and the number of propagules is greatly increased (Alleman and Hester 2011). This was seen in multiple stands on differing timelines. To account for this during vegetative growth years more outside propagules will be brought in to mitigate the lower production. As the project continues more of the wetlands will be converted and health checks of the established trees will be conducted. Additional supports or treatment will be applied when needed and on a case-by-case basis. This would run for at least 15 years with extensions due to hurricane disruption disease or other circumstances that might hinder the progress. To combat any deep freeze winter events that could cause large mortality events trees will be covered to protect against the frost in the initial stages towards the end of the project the number of trees will be too many to continue this practice. As this project would not be implemented until later in the century when winter extremes have risen freezes will be less of an issue than they currently are. Once established the artificial implementation of trees will be weaned off so the natural distribution of propagules can supplant the forests. Continued monitoring and observations will be conducted for years after the restoration to ensure the ecosystem functions properly and can become self-sustaining.

To quantify the potential cost of the implementation project the review by Bayraktarov et al. (2016) was utilized for pricing. The prices from Bayraktarov et al. (2016) were gathered from a review of 59 mangrove restoration projects in developed countries mostly the USA and Australia. The average price of 132,000 USD per hectare (adjusted for inflation) will be used to represent a medium benchmark for the project while the median price of 48,000 USD per hectare (adjusted for inflation) will be used for the low estimate. This will provide a range that will most likely encapsulate the actual price. Since operating and capital costs will increase the price 2-4 times (Bayraktarov et al. 2016) a third price was used at 525,000 USD per hectare showed the upper limits of the projected cost. With the affected area being 66,171 hectares, these totals equal: 3.2 billion USD (Low), 8.7 billion USD (Medium) and, 34.8 billion USD (High). The true price of the project will be between the medium and high dollar range due to the extreme size of the project and the long duration of the project.

Non-native species

Non-native species can cause major disruptions in any ecosystem if allowed to become established. At its core, this project is about introducing a non-native species into an established ecosystem in an effort to unseat to the native species for control of the regions space and resources. While it is non-native, black mangroves habitat range projections show they are likely to be established across the GoM by 2100 (Osland et al. 2020). Money and resources could be allocated towards preventing this migration or it can be embraced and utilized for all the potential benefits it will provide to the surrounding communities. Embracing mangroves as a non-native species could lead to other problems as well if not monitored.

The establishment of one non-native species in an ecosystem can open the door for more subsequent invasions (Hengeveld 1988). Allowing black mangroves to take hold in the HGA could lead to other non-native species that have already been seen to invade black mangroves in South Florida. Some of the potential vegetation species are *Lygodium microphyllum* (Old World Climbing Fern), *Schinus terebinthifolius* (Brazilian Pepper), and *Casuarina equisetifolia* (Australian Pine). All of these species have invaded mangrove forests in South Florida and out competed the mangroves even dominating some of the forests (Marshall 2017). If these species were to invade the mangrove forests being converted in the HGA they could have very costly effects. This would be the unintended consequence for the intended action.

. Consistent monitoring and early action are the most effective and cost friendly way of treating non-native species. The eradication and removal of an non-native species can be an extremely costly process with little success outside of isolated island ecosystems (Angeler and Alvarez-Cobelas 2005, Baker et al. 2020). Brazilian pepper trees are exceedingly difficult to remove as simply cutting them adds to the spread Florida is using small pests *Pseudophilothrips ichini* (Thrids) and herbicides to attack the root systems. the treatment of a 2,549.5-hectare area in the everglades has cost 100 million USD over the past two decades (Allen 2019). One farmer who manages 16,187-hectare farm in Southern Florida pays 250,000 USD annually to combat the non-native tree.

A study conducted by Hiatt et al. saw that for every 5 million spent on management 5,500 hectares (\$909.1 ha^{-1}) would be free from invasion when dealing with *Hydrilla verticillate* (Hydrilla). If mangroves were to be managed in a similar fashion in the study area to prevent invasions it would cost 60 million USD annually (\$909 ha^{-1} times 66,171 ha) to prevent invasions given the area to convert all 66,171 hectares. In 2019 over 100 non-native species could already be found in the Galveston bay area but very few new species have become established since 2005 (Zaveri 2020). The large amount of shipping in the area increases the chances of a non-native species being introduced into the ecosystem (Zaveri 2020). Non-native species are unfortunately an unavoidable part of today's world with global trade and private collectors and aquarists releasing species into the wild by accident or with good intentions. Non-native species are dealt with on a case-to-case basis by the threat to ecosystem and its impact on humans. Since this is a hard thing to forecast, the 60 million USD annually was used over the life of the project to monetize the potential treatment amassing a total of 900 million USD to cover the initial 15 years. this is just a simple projection without considering discount factors or inflation. This number is seen as a worst-case scenario as that much capital would not be needed at the onset of the project. In actuality the costs would increase incrementally as non-native species are discovered within the study area instead of the even annual costs projected it would be more lopsided towards the end of the 15 years.

Carbon sequestration

Carbon sequestration is a valuable ecosystem function that is found in both mangrove forests and salt marshes. The intended consequences are that it will increase the blue carbon in the area and can potentially slow climate change. The increase in blue carbon will be monetized using carbon credits at the current market value. The potential to slow climate change is not able to be monetized due to the fact that a combination of global factors that influence the rate of change, and it is not feasible to quantify the impact of this one region alone in terms of global impact. These two ecosystem types exhibit different capacities to sequester carbon in both rate and total storage (stock). Alongi (2015) found that globally mangroves store substantially more organic carbon than the natural salt marshes (739 Mg C_{org} ha^{-1} vs 334 Mg C_{org} ha^{-1}). Thorhaug et al (2019) found similar trends in the current blue carbon stocks in the GoM (386 Mg C ha^{-1} in mangroves and 206 Mg C ha^{-1} in salt marsh). The Thorhaug results was used as it relates to the exact area and species that will be incorporated in the study area. As the salt marshes are converted to mangroves the existing blue carbon will not be lost, but the ability to store more carbon will be increased. This is demonstrated in the Dontis et al. (2020) study of historical salt marsh areas that have naturally been converted to mangroves in the same manner that will be facilitated by this project. At young mangrove sites aged 1-5 years carbon stocks were measured at 34.5 Mg C ha^{-1}. Once those sites had matured to old site status aged 14+ years they measured 138.7 Mg C ha^{-1}, an increase of 402%. This can be attributed to mangroves increased storage capacity. The salt marsh sites were established and fully functional before the conversion to young mangroves and while above ground stocks might have lessened below ground stocks should not have been drastically affected.

While it has been seen that salt marsh ecosystems do sequester more carbon annually than mangroves, carbon stocks and not rates were used to monetize this benefit. This decision was made due to the fact that the HGA is not expected to be actively tracking and trading these carbon credits. Instead of estimating a smaller annual rate like would be expected a one time revenue was calculated to illustrate the increased potential earnings that the increased carbon stock offered by mangroves represents. Using the 180 Mg C ha^{-1} storage capacity difference stated in the Thorhaug study the complete conversion of estuarine wetlands to mangroves would increase to total carbon storage capacity of the area by 11.91 Tg C ha^{-1} (180 Mg multiplied by 66,171 ha). Using the rough average of carbon in December 2020 at 20 USD per ton this would equate to increasing the total storage potential by 263,000,000 USD (Deign 2020). This would constitute increased potential earnings that mangrove forests would bring to the HGA and would only be a one-time monetary benefit as the storage potential will not change unless the total mangrove acreage were to increase.

Nurseries and refugia

Wetlands play an important role in the early stages of many aquatic species life histories. They are highly productive ecosystems that can provide many resources for young vulnerable organisms. Both salt marsh and mangrove forests provide ample places to hide from predators for young fish and crustaceans. The presence of wetlands during the early stages of these creatures’ lives has been shown to increase survival rates of individuals (Octavio Aburto-Oropeza et al. 2008). During high tides when larger predators have access to the wetlands the young can find refuge among the roots and grasses until the tides recede and they can come out and forage among the protection the lower water levels provide. Nursery services provided by wetlands not only increase the stocks of inland fish species but also offshore pelagic species that take advantage of the safety wetlands provide until the young are large enough to survive in the open water (Bell 1997). Healthy fisheries can provide a large economic output to a region and provides many resources both commercially and recreationally.

The HGA is home to a large abundance of fish, shrimp, and oysters that have large economic value. The vast majority of commercial seafood exports from the area (95%) consist of shrimp, crab, and oysters (TAMUG 2010). Recreational fishing is also a large industry for the HGA with half of all Texas' recreational fishing expenses associated with the region . Fishing charters are also a lucrative industry both within the bay and offshore in the GoM. Galveston Bay is home to the third most privately owned marinas in the United States (Smith). The area is able to support all of this fishing due to its high fish stocks and high biodiversity. Over 100 species of fish can be regularly found in and around Galveston Bay and Galveston has been listed as the "Third best saltwater fishing city in the United States" by sportfishing publications (Lucey 2020). Large stocks of shrimp, fish, and crabs need to be supported for the region to continue to capitalize on the commercial and recreational opportunities.

Mangroves and salt marsh can largely contribute to fisheries and increase their economic values by the services they provide. Rozas et al. (2005) compared salt marsh areas with adjacent open shallow water/ beach areas in Galveston Bay to see the effect on fisheries that wetlands played. They estimated that wetland areas can support 9 to 14 times more white shrimp, 3 times the amount of brown shrimp, and more than double the number of blue crabs than the areas where wetlands are absent (Rozas et al. 2005). Similar numbers can be expected from any mangrove that are established in the area as well. A Study done by Frederick Bell (1997) on the value that salt marshes provide in Florida established a value of 36,000 USD (adjusted for inflation) per hectare of fringe yearly. Oropeza et al. (2008) found that the median benefit value of mangroves in Mexico on the fisheries was 48,000 USD (Adjusted for inflation) per hectare of fringe yearly. This is a difference of 12,000 USD and this is the number that will be used to put a valuation on this service. Since this service is only provided by the fringe hectares or the mangroves on the outer seaward edge as this is what the organisms can access the total acreage needs to be adjusted. For this we will assume that the 66,171 hectares replaced will be a uniform square a perimeter being 1030 hectares. Since only half of the square would be considered fringe in contact with the water half of this value or 515 hectares will be used to calculate the total value. This equates to 6.2 million USD yearly in benefits to the local fisheries. While the actual fringe will be much larger in reality as mangrove forests are much more rectangular in shape, using a square will be accurate enough for this estimation. Further analysis can incorporate shapes and models that more accurately represent the coastline and affected area.

Shoreline management

Sea-level rise and erosion are a large threat to the HGA when addressing the future. The local area government is currently looking at three distinct approaches: protection, accommodation and, retreat. This paper would constitute a protection plan by applying a living ecosystem as coastal protection. Accommodation plans are just masking the problem by building stilt houses and disclosing information during real estate transactions. Retreat options are just as it sounds retreating inland to get ahead of the problem. Retreat is the safest most surefire option since it removes the risk, but it is extremely costly and will be met with tremendous public outrage and apprehension (McLaughlin et al. 2018). The majority of the current protection plan posed by the Army Crop of Engineers are to implement more hard structures and use dunes as living protection at the cost of wetlands. By using mangrove wetlands as the living protection, you can utilize their natural functions to combat SLR and shoreline erosion.

Erosion is rampant in this area between large storm events taking massive swaths of sediment at once and long-term sustained erosion due to wave action. In 2008 during Hurricane Ike 77 million m^3 of sand was lost to erosion, this equates to 2.5 billion USD and 65 years of natural erosion for the area (Randall 2013). Natural erosion rates for the counties of interest are not much better, 92 km of the 157 km (58%) of coastline are experiencing critical rates of erosion that range from 0.85 m to 2.99 m in annual erosion (Gillen 2015). This sort of substantial sediment loss is not sustainable without intervention. The current salt marsh ecosystems in the area are also being lost to erosion due to insufficient sediment supply (Ravens et al. 2009). Chen et al. (2018) found that salt marsh slightly out completes mangroves for direct sediment capture in shallow water environments but postulates that this could be due to the fact that the mangroves studied were not fully grown and did not have aerial roots. Seedlings outperformed grasses with similar stalk sizes under the same observation. This implies that even if salt marshes were converted to mangroves the wetlands would still be under threat without outside intervention in the form or sediment supply whether it be through extraction from dunes or imported from a third party.

Galveston Bay has experienced a steady average total rise (sum of SLR and subsidence) of 6.84 mm/yr over the last 106 years (GDHHB 2019). If this were to continue we would see a rise of at least 0.684 m over the next century this is consistent with the estimate given in McKee et al. (2011). Sea-level rise is projected to accelerate in the coming decades so the actual rise in Galveston Bay will be higher than the Mckee estimate. Black Mangroves in Southwest Florida were observed by Cahoon et al. (1997) to be able to rise at rates equal to SLR. McKee et al. (2018) studied the effects on vulnerability of salt marsh and black mangroves to SLR over a six-year period in the Mississippi River Delta. The study found that while both systems exhibited vertical accretion at equivalent rates the mangroves had higher elevation capital. While this does not mean that mangroves in the area are any less vulnerable than the salt marsh it hints at more longevity due to the higher elevation. There is no evidence of a significant difference in response to SLR or control of erosion between the two ecosystems. Due to insufficient sediment being equally detrimental to both mangroves and salt marshes, the replacement cost would be equal in both cases. Since both of these systems capture sediment at roughly the same rates by replacing the marsh with mangroves will not solve the sediment deficiency problem. Therefore, no monetary cost or benefit can be derived in the aspect of shoreline management without further investigation in the HGA.

Storm surge / wave attenuation

Hurricanes and storm surges have decimated the HGA dating back to a storm that wrecked a Spanish ship off the coast off Galveston island in November of 1527 killing 200 (Roth 2012). Since then, there have been many more storm events to hit the area with the deadliest hurricane in recorded history striking Galveston in 1900 and killing an estimated 8,000 people (Roth 2012). As the years progressed the loss of life has been minimized but the monetary damages have grown exponentially as technology and infrastructure has increased. Hurricane Harvey in 2017 is the second costliest storm valued at 125 billion USD in damages, and the average U.S. hurricane cost from 1980-2018 is 21.5 billion USD (Frohlich 2018). Storm surge and flooding are the most damaging aspects of a hurricane (UCAR 2021). Putting protections in place to mitigate storm surge should be a high priority in places like the HGA. From 2015-2019 Houston experienced five storms that produced 500-year flood events (Ahmed 2019). With projections that storms will increase in intensity as climate change progresses this is a severe warning sign for regions that are frequently disrupted to get protections in place as soon as possible. A study by Davlasheridze et al. (2019) found that the implementation of a coastal spine consisting of hard structures would prevent 11.78 billion USD in damage during a 500-year storm event in the HGA (33.43 billion in damages without protection and 21.64 billion with protection).

Using a living spine in the form of mangrove forests will also prevent losses from hurricane damage as well. The ability of mangroves to protect infrastructure from hurricanes was investigated by Del Valle et al. (2020), and the level of protection was causally related to the width of the forest. They saw that damages were completely mitigated in instances where the forest width was 1 km or wider. Little of the heavily developed western shore of the bay can support forests of this width but will still benefit from mangroves wave attenuation functions. Sea, Lake and Overland Surges from Hurricanes (SLOSH) modeling can be used to analyze historical data from past hurricanes to determine trends in storm surge heights based on strength and angle of approach. SLOSH models from Hurricane Ike 2008 and 1900 Galveston Hurricane show vastly differing storm surges within the bay with maximum surge heights reaching 1.8-2.4 m and 5.5-6.1 m respectively. It should be noted that SLOSH modeling does not account for wave action on top of the storm surge or flooding from precipitation, so the actual events likely displayed higher levels of inundation.

While these two storms are among the strongest to hit the HGA in recorded history the area has a long list of historical storms. Analyzing data provided by NOAA covering the hurricane and tropical storm events in the HGA from 1886-2019 the following trends were seen (NOAA 2008). The average frequency of a storm event during the 133-year period was 1.83 years and the average span between hurricanes was 3.23 years. During this span there were also only eight instances where a gap between storms was five years or more (8 years being the longest gap). This constant barrage of storms illustrates the need for storm surge protection and the importance to protect the shorelines. A study by Siverd et al. (2020) has estimated that along the coast of neighboring Louisiana wetlands approximately 2,300 USD per hectare per year (adjusted for inflation) is saved due to hurricane surge protection, the majority of these wetlands being salt marshes. During Hurricane Irma in 2017 it was found that mangroves were able to provide 7,500 USD per hectare in risk reduction (Narayan et al. 2019) in south Florida. In the absence of storms provides 540 USD per hectare annually to the region in natural non storm related flood protection. To monetize this an estimate range was created using the Siverd number times the number of hectares to be converted this is the low estimate. To obtain the high range the Narayan number was divided by the average span of storms to provide a per year basis ($4,000 per hectare per year) and was then multiplied by the numbers of hectares to be converted. Based on these calculations, the estimated range of storm surge protection by wetlands was found to be 152.2-267.7 million USD annually. The low estimate can be compared roughly to the current benefits seen by the HGA wetlands as the Siverd number does not differentiate between mangrove and marsh ecosystems. When adjusted to represent the actual estimated benefit due to the conversion to mangroves for storm surge risk reduction will be 0-112.5 million USD annually in additional benefits. The 0 figure represents the Siverd number since that is essentially the same as the benefits that the current slat marsh provides and the 112.5 million USD uses the Narayan figure and illustrates the largest possible increase in benefits that could be expected from mangrove implementation.

Total Cost Analysis

The total projected net cost for the implementation of mangroves in the HGA was calculated for each implementation cost scenario and all of the other costs and benefits (Table 3). The totals are presented in a wide range as to drive home the fact that this is an estimation and there is a high degree of variability between the price points chosen and actualities. This large price window also increases the likelihood that the actual total will lie within the range. All of the totals were calculated using the "Mangrove High" yearly rate for storm surge. The differentiating variable in the "Low" "Medium" and "High" totals are the corresponding implementation cost used all of the other benefit prices were constant for all 3 projections. The high total cost is approximately 33.5 billion USD over the 15 year span proposed in the plan with the medium and low totals coming in at 7.5 billion USD and 2 billion USD respectively. After this initial investment, benefits will be valued at least 58.7 million USD (2021 values) annually for each scenario as the only change between the three is the implementation costs. It should be noted that these totals do not account for inflation or include any sort of discount factors when projecting for the full 15 years. While these numbers are high it should still be considered a viable option. The currently proposed protection plan is valued at 26 billion USD which is comparable with the high estimate total and that plans only addresses storm surge mitigation not any of the other climate change concerns. Local and federal governments would provide the majority of the funding through various grants and programs. The Clean Water State Revolving

Fund would be an example of a program that could help alleviate costs. Supervised volunteer work and donations would lower labor costs. This is a highly economically viable option that should be investigated further using more region-specific modeling and pricing as the monetary benefits will only increase in value as climate change progresses. A way to reduce costs would also be to scale back the size of the mangrove plantation areas. By identifying specific targeted areas that would greatly benefit from mangroves the project could be tailored to areas of high need. This would decrease costs by focusing on the most important areas first with the option to expand in the future once funding becomes available.

Table 3: Profit and loss table showing how much each service costs over the life of the project. Net totals are located at the bottom

Service	**Price**	**Units**	**Frequency**	**Total**	**Project 15yr Total**
Implementation Cost (Low)	48,000 USD ha^{-1}	66,171 ha	Once	\$3,176,208,000.00	\$3,176,208,000.00
Implementation Cost (Medium)	132,000 USD ha^{-1}	66,171 ha	Once	\$8,734,572,000.00	\$8,734,572,000.00
Implementation Cost (High)	525,000 USD ha^{-1}	66,171 ha	Once	\$34,739,775,000.00	\$34,739,775,000.00
Invasive Management	909 USD $ha^{-1} yr^{-1}$	66,171 ha	Yearly	\$60,000,000.00	\$900,000,000.00
Carbon Sequestration	20 USD ton^{-1}	11.91 Tg C	Once	\$263,000,000.00	\$263,000,000.00
Nursuries and Refugia (Used)	12,000 USD fringe $ha^{-1} yr^{-1}$	515 ha	Yearly	\$6,200,000.00	\$93,000,000.00
Storm Surge (Wetlands / Mangroves Low)	0 USD	66,171 ha	Yearly	\$0.00	\$0.00
Storm Surge (Mangroves High)	1700 USD $ha^{-1} yr^{-1}$	66,171 ha	Yearly	\$112,500,000.00	\$1,687,500,000.00
				Low	**-\$2,032,708,000.00**
				Medium	**-\$7,591,072,000.00**
				High	**-\$33,596,275,000.00**

Which regions of the Houston Galveston area would benefit most from mangrove forests

Coastal protection needs with respect to SLR and storm surges are determined by factors such as topography, elevation, and coastline shape. Areas in the same region can have different threat levels based on these characteristics. Being able to differentiate between areas of varying needs of protection would be a valuable tool for land managers and planners. Using Spatial analysis has been proven to be a good way to highlight trends within a region (Mafi-Gholami et al. 2020). Model types that specialize in analyzing discreet boundaries such as fuzzy logic can be useful to determine site suitability and predict the locations of animal habitats (Hattab et al. 2013)

The hypothetical plan highlighted in this paper is a universal conversion of estuarine wetlands to mangrove forests in the HGA. While every area would benefit from mangrove protection, being able to prioritize areas can be important for the planning stages and any potential revisions to implementation. Costs also vary depending on the level of alteration and existing land use. To provide further insight into where to target mangrove conversion in the HGA a GIS map (Figure 4) was created to highlight the areas of the most ecological need while also considering the cost of alteration. This expands not only to the estuarine wetland ecosystems but to all of the coasts within the study area. Being able to assess the entire area based on these criteria can show which areas should be considered to expand the plans and which area of estuarine wetlands would not be that beneficial to convert. Knowing this information would help better allocate resources to ensure the plan has the biggest chance at success. Certain areas highlighted on the map that will be examined in further detail are the bay side of Galveston

Island, the northeast section of Galveston Bay, by Baytown, and Smith Point. Other areas that were identified as areas of need are located within national wildlife preserves and have been excluded due to the low possibility of conversion approval. These are the Brazoria, Anahuac, and San Bernard Nation wildlife refuge parks. The current plan proposed by the Army Corp of Engineers in February 2021 will also be analyzed to see what protections it offers and if it addresses any of the areas that have been pointed out on the map.

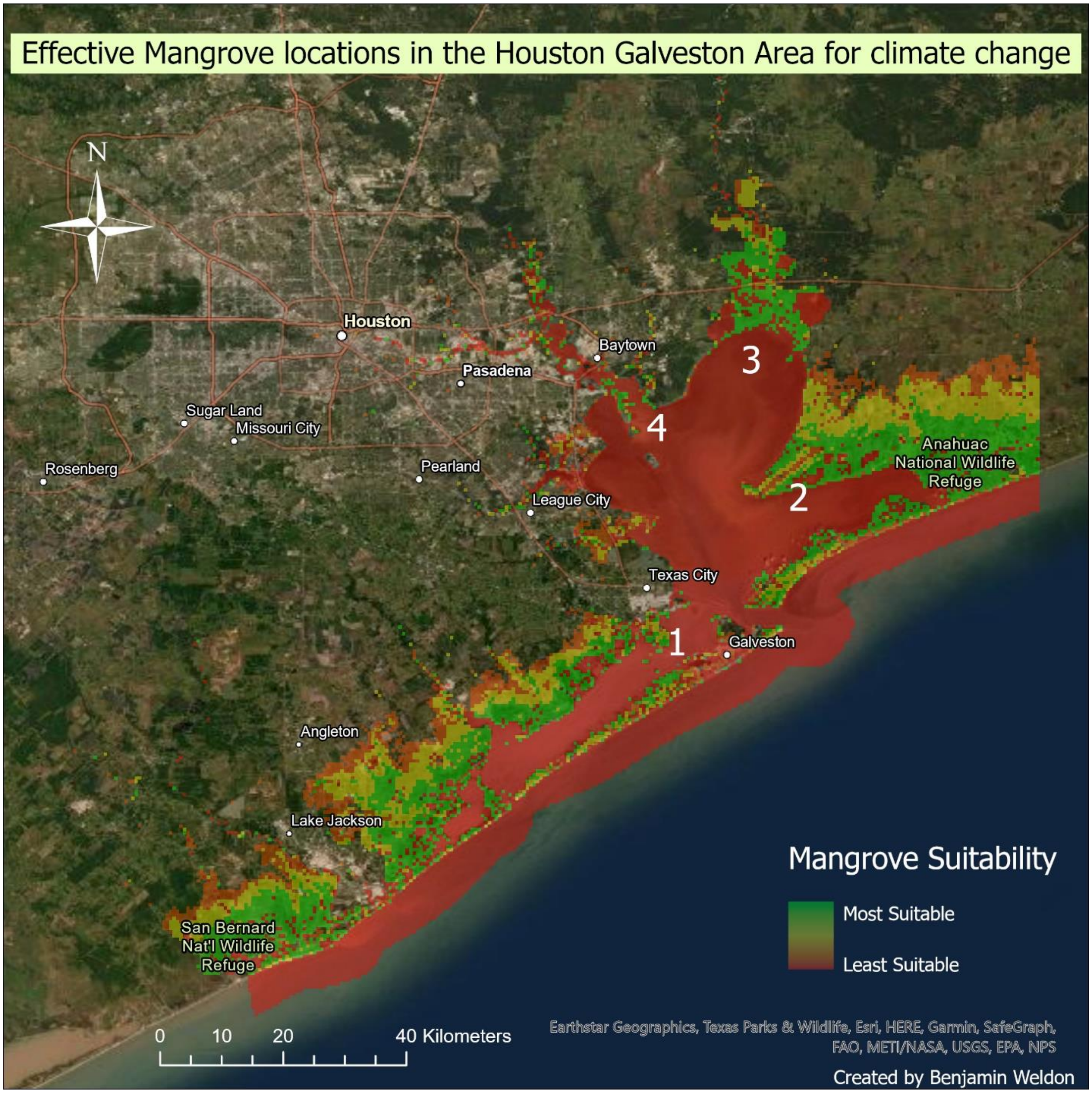


Figure 4: Fuzzy logic map that shows the areas in the study area where mangroves would be of high ecological value with factoring in costs. the most suitable sites are in green and the least are in red. The highlighted areas are 1. Galveston Island 2. Smith Point 3. Northeast corner of the bay 4. Baytown area.

Galveston Island

Galveston Island is located on the western side of the mouth of Galveston bay and is home to about 50,000 people. It measures 47 km long and at its widest point is 4.8 km (TSHA 2018). It is extremely susceptible to SLR as the average elevation on the island is only 2 m (TSHA 2018). its current defense is a sea wall on the gulf side that was constructed after the 1900 hurricane that devastated the island. The map has identified Galveston Island as an area of importance due to its low elevation. Specifically, the bay side of the island as placing mangroves on either side of the sea wall that spans the gulf side would have no significant impact. This is due to the walls presence and effect on natural tidal action placing mangroves behind the wall would devoid them of water being blocked by the wall and on the gulf side of the sea wall there is not enough space to plant the mangroves without them drowning. The westward side of the island also has experienced high rates of erosion over the last 50 years averaging between 1.5-3 m/year (Gillen 2015). During hurricanes this can be exacerbated as the storm surge that fills the bay drains out through the narrow channel between the backside of the island and the mainland. As this large volume of water exits the bay it strips the area of large amounts of sediments (Coastalstudy.gov 2021). The presence of mangroves on the bay side can help to stabilize the sediment and slow the exiting water mitigating levels of erosion after major storm events. The mainland coast across from the island also suffers from this phenomenon and thus is viable for mangroves as dictated by the map as well.

Smith Point

Smith Point is a small unincorporated area on the eastern side of the bay to the west of Anahuac national wildlife refuge. It consists of a high central ridge with lower lying wetlands on either side. At 1 m rise all but the ridge will be lost and at 3 m everything will be inundated. The ecosystems surrounding the ridge are primarily made up of salt marsh that line the bay. While this area only houses approximately 250 people the ability to convert into one large continuous mangrove forest is extremely valuable as mangrove services function more efficiently at higher densities and without fragmentation (del Valle et al. 2020) This area could help to drastically reduce storm surges that pass through on their way to more populated areas on the northern side on the bay with mangrove implementation.

Northeast section of the bay

The northeast section of the bay is home to a few small towns surrounded by large swaths of agricultural land. The map has identified a large coastal area that would benefit from mangrove implementation that is currently a mixture of estuarine and woody wetlands. Projections of SLR for 1 m would completely inundate this area with the 2 and 3 m projections affecting the surrounding developments emphasizing the need for protection. Historical SLOSH modeling also shows that during Hurricane Ike (Figure 5) and the Galveston 1900 storm (Figure 6) this area received surges of 3.6 and 4.5 m respectively. These models show the peak depths of the storm surges from both of these hurricanes that passed over the area. The actual surges were most likely higher than what is shown as these do not account for wind driven storm surge heights Being able to mitigate the SLR and storm surge in this area would not only protect the human communities around it but also provide protection to the agricultural lands. Saltwater intrusion can cause one fertile cropland to become unsuitable for agricultural growth causing large economic losses. When saltwater evaporates in cropland the salts are left behind in the soil and inhibit growth to all but salt tolerant vegetation. The salts can also chemically react with the nutrients in the soil and mobilize them as the salt water recedes it pulls the nutrients with it and can cause water quality problems such as eutrophication and algal blooms (USDA 2019). Saltwater can also invade groundwater and taint reserves that are utilized for human consumption (USDA 2019).

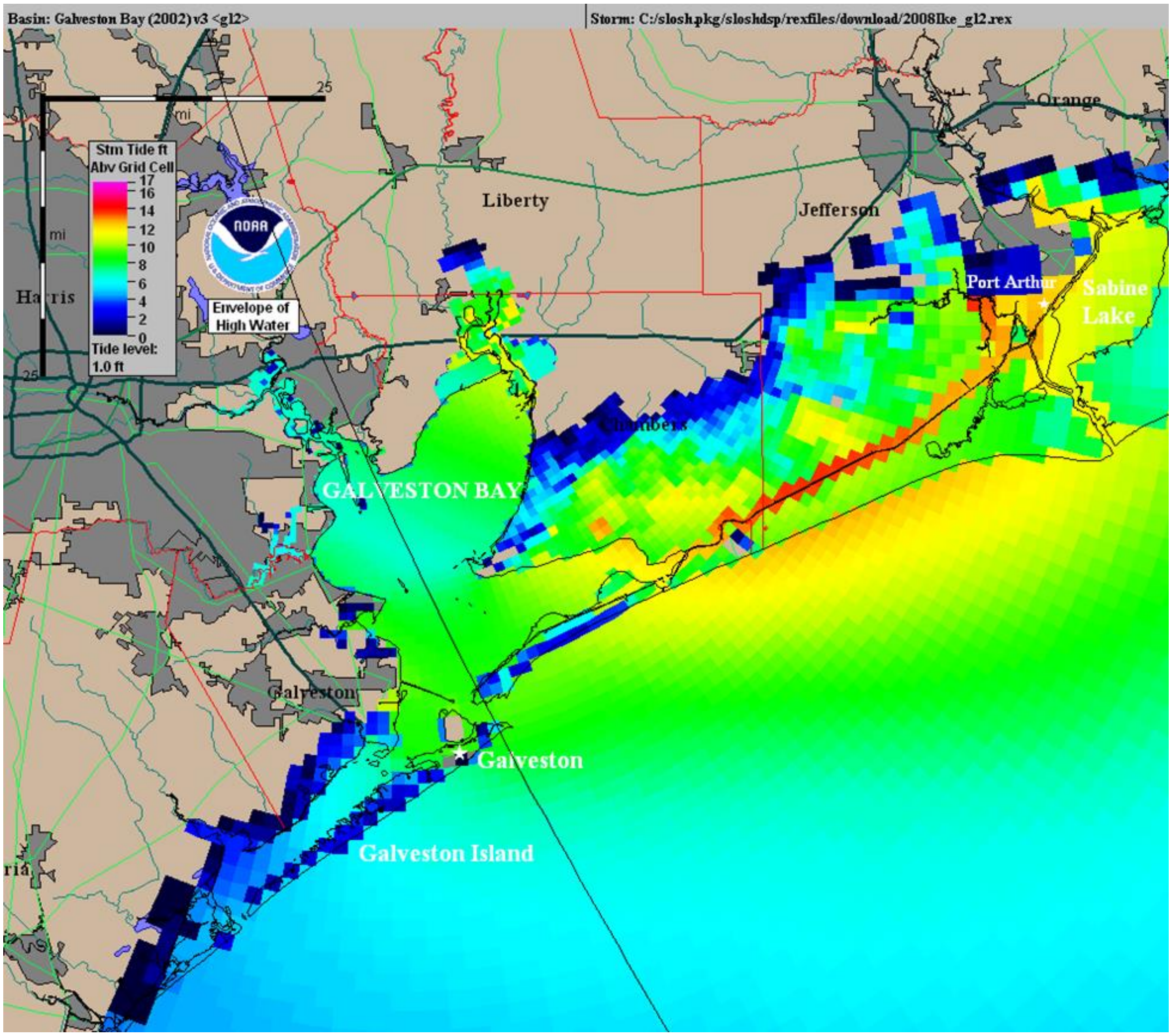


Figure 5: SLOSH model for Hurricane Ike in 2008. This image shows the storm surge maximums during the event. Images provided by NOAA.

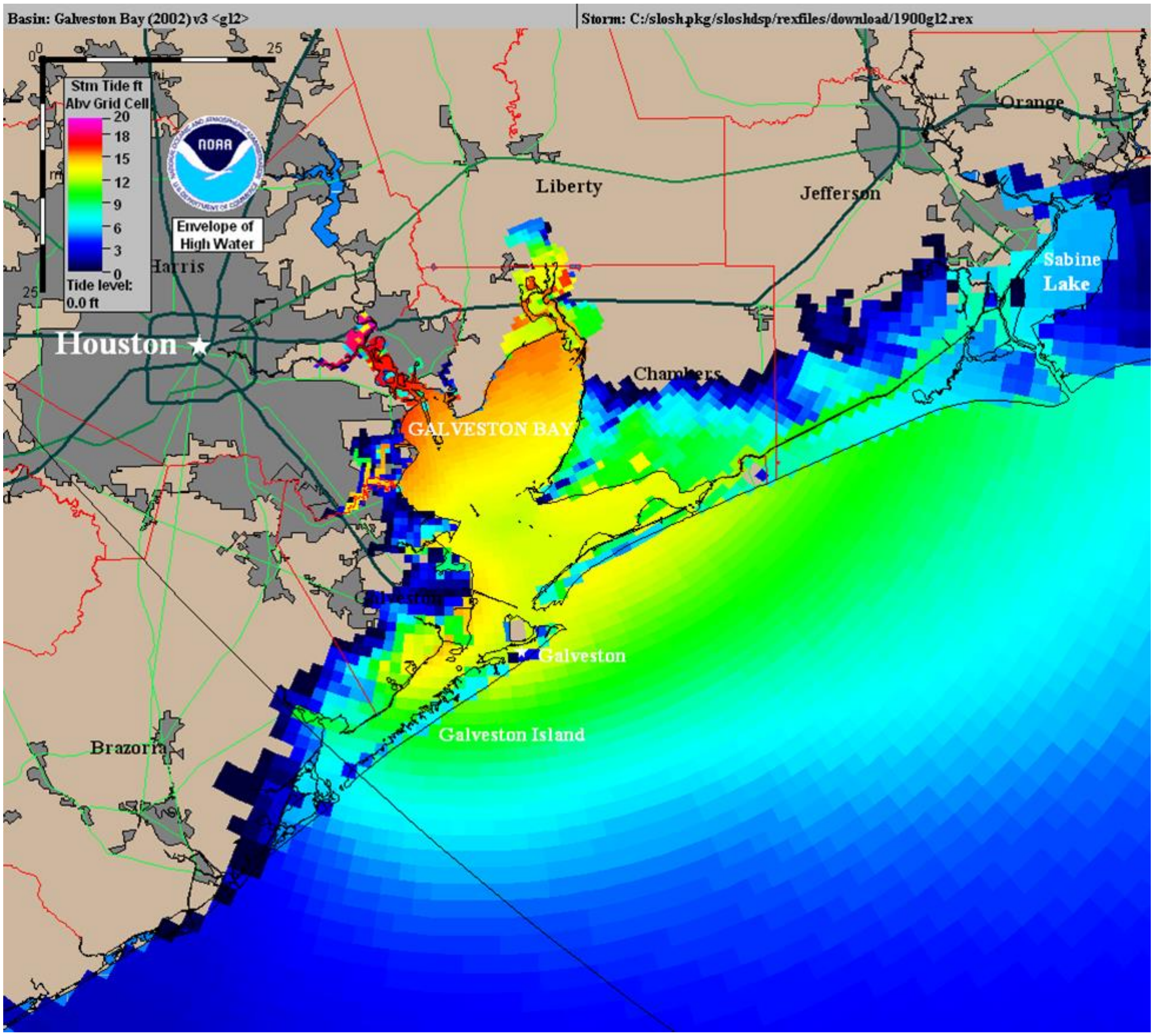


Figure 6: SLOSH model for the Galveston Hurricane in 1900. This image shows the storm surge maximums during the event. Images provided by NOAA.

Baytown

The last region highlighted in the map in the smallest in size but is of great economic importance. Baytown is on the northwestern region of the bay where the water goes through a natural funnel on the way to Houston. This funneling effect can have major consequences for storm surge increasing the height from what is seen in the open bay. The Galveston 1990 SLOSH model (Figure 6) demonstrates this as this area saw a surge of 5.5-6 m. While the planted grove of mangroves would not be substantial in size it would still be effective in slowing some of the water and reducing future storm surge. The surrounding region is highly populated and is home to many industrial complexes (Figure 7). A large number of these facilities are located around the suggested area of protection need. If one of these facilities were to be compromised it could cause major health and economic costs to the community and should be avoided at all costs.

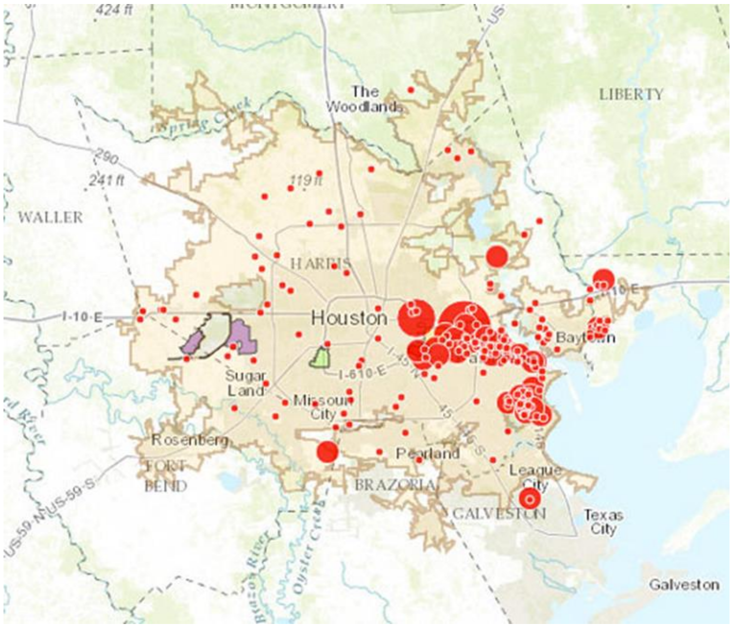


Figure 7: Map showing the location and density of dangerous chemical facilities in the HGA the small dots represent 1 facility and the larger circles are 6-48 facilities.(Gerbode 2016)

Current protection plan for the area

The Army Corp of Engineers released their protection plans for the HGA in February of 2021. All of the following information has been collected from them and the coastalstudy.texas.gov website. The Plan is projected to cost 32 billion USD and take over 15 years to complete. There are three main parts to the plan (Figure 8): a ring barrier system around Galveston, a bay side approach, and a gulf side approach. The proposed plans in Galveston are to improve the 16 km seawall and raise it in height to protected against storm surge on the gulf side. To protect on the bay side of the island a ring barrier system is proposed that will consist of 29 kms of floodwalls, levees, gates and pumps with a maximum height of 4.3 m. The gates are proposed to remain open until a storm threat appears to keep life and navigation as consistent as possible. The gulf side proponents of the plan are the creation of a road gate system from Bolivar Peninsula to Galveston Island covering the entire entrance to the bay.

This road gate will consist of four sections. The first being two large gates roughly in the middle of the bay opening. The current channel with be expanded and a second will also be dredged they will measure 198 m wide and 18.2 m deep. The gates will sit in three artificial islands that will be created for this project. When a storm comes the gates will close the channels and pumped full of water causing them to sink. When sunk only 6.7 m of the gates will be above water to lessen surges. Next to the channel gates will be smaller will be 38.1 m long and also be 6.7 above water when closed. Shoreward of these will be a series of 15 vertical lift gates (5 on the western side 10 on the eastern) these will be 91.4 m in length and rise to a height of 30.5 m. these will remain open until a storm threat. On the Bolivar Peninsula side (eastern shore) there will be 6 Shallow Water Environmental Gates (SWEG) that are 4.9 m square to allow for protection in the shallower waters and still allow for marine life to pass in and out of the bay using the shallower waters. Lastly to connect to the eastern shore a combi-wall will be placed that is 6.7 m high and 1.52 km long. Additionally on the gulf side of the bay 69.2 km of beach and dune restoration is planned with the dune structure consisting of two dunes 3.6 m and 4.2 m tall (seaward and landward respectively) with 2.4 meters in between the two dunes.

The bay side plans for the project include the addition of two surge gates to better control the release of water that would make it into surroundings facilities and residential areas. Six new pump stations would also be added to move water off of the land when inundation does occur. It mentions that 10% of the budget will be allocated for ecosystem restoration. Based on the plans these ecosystems will include marsh wetlands, oyster beds, beaches, and dunes. The exact acreage per ecosystem type was not found. While there are some “soft” components to this project (dune and ecosystem restorations) it is mostly a hard structure engineering project and the opposite action plan than the one that is discussed in this paper. It does however address the problem of storm surge as the water enters the bay instead of when it reaches the shores as is the case with mangroves.

The Army Corp of Engineers proposed plan only addresses one of the areas identified by the GIS analysis. The pumps and the ring barrier on Galveston Island will help with the problem of erosion due to receding water levels after storm events. It does not provide support for the other areas of need that were previously discussed. It does however address the problem of storm surge as the water enters the bay instead of when it reaches the shores as is the case with mangroves. Sea-level rise issues will only be mitigated through the dune and ecosystem restoration the exact extend is unknown at this time due to the plans not being finalized.

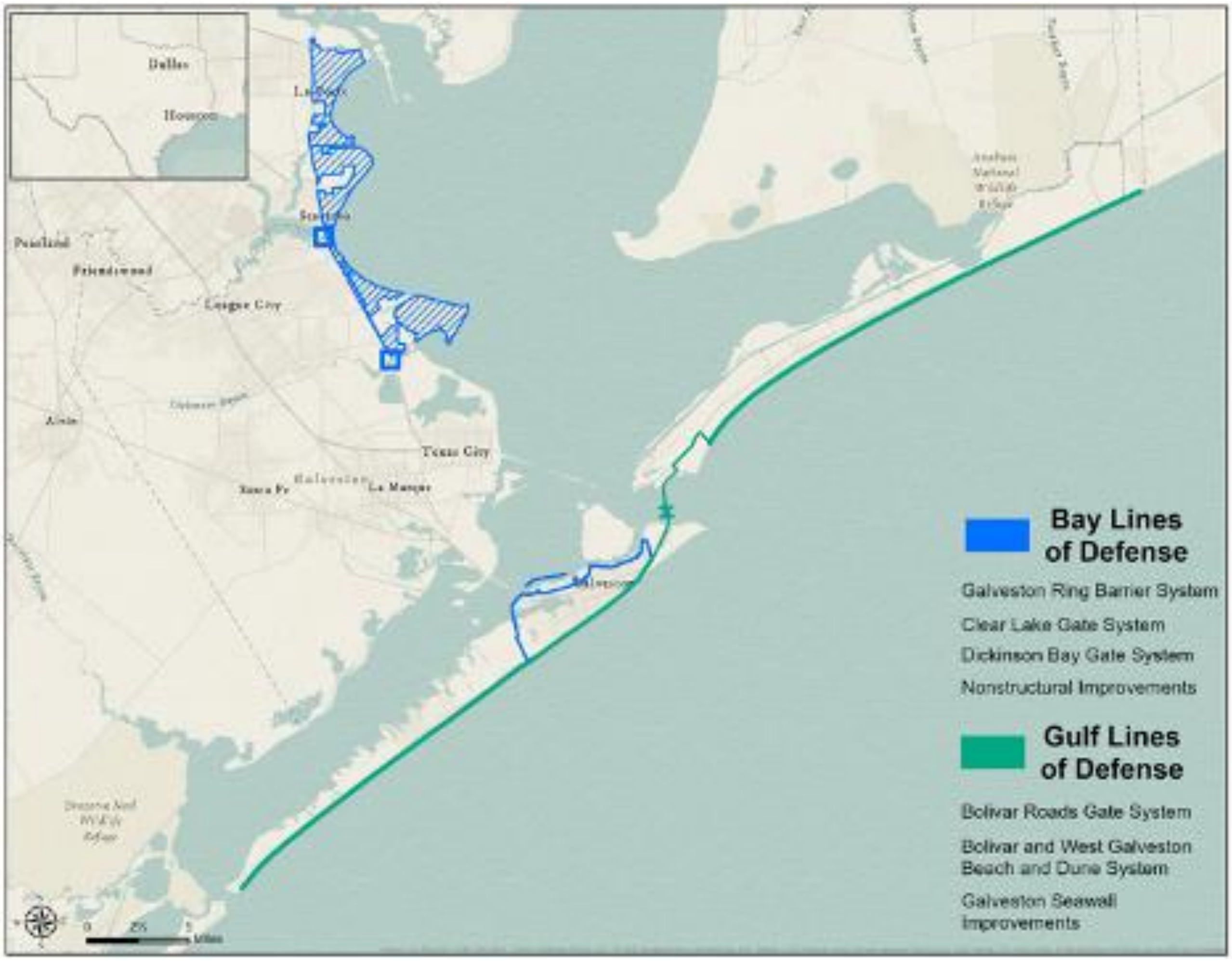


Figure 8: The proposed protection plan by the Army Corp of Engineers 2021

Discussion and Recommendations

This analysis has shown that the implementation of mangroves within the HGA is a viable future option if climate change were to progress to a level that would allow for such measures. The costs are comparable with the current protection plans for the region and will provide a more diverse protection against multiple threats. Mangroves will continue to provide annual monetary benefits to the HGA as long as they are present and functional as ecosystems. With the current habitat projections and the knowledge that mangroves will outcompete salt marsh once they migrate into the area mangrove forests should be seriously thought of as a potential climate change mitigator for the HGA. With this in mind there are a few recommendations that would benefit the area currently and help to strengthen this argument based on the finding from both the economic analysis and the GIS analysis.

I would recommend that this economic analysis be redone with both a more comprehensive look at all of the ecosystem benefits that will be altered by the plantation of mangroves and with more region-specific economic modeling. This paper has analyzed the big-ticket benefits in terms of economic endpoints but by conducting a more intensive look at the numerous smaller revenue benefits the net total cost could drastically be altered. For instance, with erosion mitigation this would improve water quality and recreational activities such as swimming and boating. The HGA has the third most privately owned marinas in the country, this seemingly small benefit could lead to a large influx in cash. Even with one or two more boating days a year per vessel this will lead to rises in fuel purchases, boating supplies, and strain on motors which require repairs. If the vessel is used for recreational fishing then more tackle, more licenses, more charters etc. will be purchased. There are multiple seemingly innocuous economic endpoints for each consequence of the main action (mangrove plantation) and other consequences not examined in this paper. All of these hidden dollar amounts whether they be costs or revenues add up quickly and can alter the net costs drastically. By incorporating these variables in further evaluations, the true cost of this project can be more accurately represented.

Applying differing economic pricing models and tailoring them specifically to HGA can also drastically actualize the total cost of the project. This paper utilized benefit transfers to generate all of the pricing and while this is a valid and accepted pricing method it does have its limitations (EPA 2002). The more differences between the reference site and the study area the more probable that the pricing will not encompass all aspects of the benefit being examined. These can be physical differences such as location or they can another characteristic such as the age of the study that the pricing is being transferred from. For instance, the Frederick Bell paper was published in 1997 and the pricing within it was taken from 1984. While these prices have been adjusted to account for inflation there are other aspects that cannot be modernized so easily. The numbers were based on a willingness to pay survey conducted in Florida forty years ago. In that time the general public's perception of wetlands ability to contribute to fisheries might have changed and they would be willing to pay more. There could also be ideological differences between Floridians and Texans when it comes to the way they value these resources. The Bell paper is a completely acceptable way to price this service, but a more accurate representation would be to conduct a new willingness to pay study with the residents of the four counties that will be directly affected. The tradeoffs of getting this more accurate price are that it would cost time and money to perform this.

Changing pricing assumptions about the study area would also lead to more effective modeling. To get a workable acreage of fringe mangroves the assumption was that the entirety of the mangroves would be in a perfect square. In reality we know that the mangroves will exhibit a more dynamic and fluid shape mimicking the coastline requiring multiple equations and summing them to get a total amount of fringe hectares that will more accurately represent the real-world end product. Again, the tradeoffs would be increased costs and time to do so. These two adjustments can be applied to all aspects of the economic evaluation to reduce the variation between the actual cost and the project costs helping decision makers make the most informed choices they can.

Utilizing the areas that have been highlighted in the GIS analysis should be taken and incorporated into the implementation plans to tailor the plan to areas of most need while still managing costs. The hypothetical plan in this paper looked at replacing all of the estuarine wetlands within the four counties. The GIS analysis was able to show areas in where it might not be as profitable or plausible to convert estuarine wetlands to mangroves, the three national wildlife refuges would be a good example of this. Ecosystems were highlighted that would be beneficial to convert to mangroves that were not included in this plan analysis. Sandy dunes and shrub/grasslands both were identified in the map as being very suitable candidates for mangrove plantation with future climate altered conditions being considered due to their physical location within the region and low alteration costs. Excluding these nontarget estuarine wetlands (wildlife refuges) and including the other ecosystem types that have been identified as viable candidates in the next project analysis can better mimic real-world conditions that we would see if the plan were to come to fruition. This would in turn lead to more accurate hectare counts and better economic assessments giving credence to this as a realistic option that should be considered an alternative to address future climate change concerns in cities along the GoM. This sort of analysis could also be modeled for other cities that border the GoM as well such as New Orleans Louisiana and Mobile Alabama.

While the implementation of this proposal is entirely contingent on an increase of extreme winter temperatures of 2 to 4°C which will not be reached until later this century certain actions can still be taken in the immediate future. Sea-level rise and increased storm intensity will be felt incrementally long before the shift in winter extremes is reached that would allow mangroves to permanently thrive in the area. The areas of importance noted in the GIS map will still be of ecological significance to land managers. Under current climate conditions salt marshes are still the dominate coastal wetland in the area and can provide immediate protection to the HGA. Putting resources into these areas to make sure that there are healthy and functioning coastal wetlands will still benefit the HGA as conditions gradually change. As stated earlier salt marsh provides many of the same benefits that mangroves do and at these lower levels of SLR and less intense hurricanes they can provide substantial results to the area while preserving the natural ecosystems and biodiversity.

Once it becomes apparent that climate change with cross this thermal threshold that will allow annual mangroves without the threat of freeze mortality then this contingency plan should kick in. With the increased ability for mangroves northward expansion and the reduced resiliency of both coastal wetlands due to fragmentation. I would argue that preemptive artificial establishment of mangroves would be advantageous to coastal cities for protection. Especially during a time when it would be most beneficial to already have these ecosystems established and fully functional. The extra storage capacity to sequester carbon provided as the wetlands transition from marsh to mangroves should not be undervalued as a means of mitigation as well to attempt to slow detrimental climate effects even further.

LITERATURE CITED

Ahmed, A. 2019. Tropical storm imelda will likely be southeast texas' fifth 500-year flood in five years. **2021**:*Texas observer*.

Alleman, L. K., and M. W. Hester. 2011. Reproductive Ecology of Black Mangrove (Avicennia germinans) Along the Louisiana Coast: Propagule Production Cycles, Dispersal Limitations, and Establishment Elevations. *Estuaries and coasts* **34**:1068-1077.

Allen, G. 2019. Florida researchers use pests to help control pesky brazilian peppertree plant. **2021**:*National public radio*.

Alongi, D. M. 2015. The impact of climate change on mangrove forests. *Current Climate Change Reports* **1**:30-39.

Alongi, D. M. 2020. Carbon balance in salt marsh and mangrove ecosystems: A global synthesis. *Journal of marine science and engineering* **8**:767.

Amadeo, K., and E. Estevez. 2020. Hurricane harvey facts, damage and costs. **2021**:*The balance*.

Angeler, D. G., and M. Alvarez-Cobelas. 2005. Island biogeography and landscape structure: Integrating ecological concepts in a landscape perspective of anthropogenic impacts in temporary wetlands. *Environmental pollution* **138**:420-424.

Anneboina, L. R., and K. S. Kavi Kumar. 2017. Economic analysis of mangrove and marine fishery linkages in India. *Ecosystem services* **24**:114-123.

Armitage, A. R., C. A. Weaver, J. S. Kominoski, and S. C. Pennings. 2020. Resistance to hurricane effects varies among wetland vegetation types in the marsh–mangrove Ecotone. *Estuaries and coasts* **43**:960-970.

Bayraktarov, E., M. I. Saunders, S. Abdullah, M. Mills, J. Beher, H. P. Possingham, P. J. Mumby, and C. E. Lovelock. 2016. The cost and feasibility of marine coastal restoration. *Ecological applications* **26**:1055-1074.

Bayraktarov, E., S. Brisbane, V. Hagger, C. S. Smith, K. A. Wilson, C. E. Lovelock, C. Gillies, A. D. L. Steven, and M. I. Saunders. 2020. Priorities and motivations of marine coastal restoration research. *Frontiers in marine science* **7**:11-21.

Bell, F. W. 1997. The economic valuation of saltwater marsh supporting marine recreational fishing in the southeastern United States. *Ecological economics* **21**:243-254.

Bhatia, K., G. Vecchi, H. Murakami, S. Underwood, and J. Kossin. 2018. Projected response of Tropical cyclone intensity and intensification in a global climate model. *Journal of climate* **31**:8281-8303.

Birch, A. 2020. The importance of mangroves. **2021**:*Nature conservancy*.

Bridges, L. 2019. Petrochemical & plastics industry. **2021**:*Colliers*.

Cahoon, D. R. 2006. A review of major storm impacts on coastal wetland elevations. *Estuaries and Coasts* **29**:889-898.

Cahoon, D. R., K. L. McKee, and J. T. Morris. 2020. How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuaries and coasts* :online.

Cahoon, D., and J. Lynch. 1997. Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, U.S.A. *Mangroves and salt marshes* **1**:173-186.

Castañeda-Moya, E., V. H. Rivera-Monroy, R. M. Chambers, X. Zhao, L. Lamb-Wotton, A. Gorsky, E. E. Gaiser, T. G. Troxler, J. S. Kominoski, and M. Hiatt. 2020. Hurricanes fertilize mangrove forests in the Gulf of Mexico (Florida Everglades, USA). *Proceedings of the National Academy of Sciences of the United States of America* **117**:4831-4841.

Chen, Y., Y. Li, C. Thompson, X. Wang, T. Cai, and Y. Chang. 2018. Differential sediment trapping abilities of mangrove and saltmarsh vegetation in a subtropical estuary. *Geomorphology* **318**:270-282.

Das, S., and A. Crépin. 2013. Mangroves can provide protection against wind damage during storms. *Estuarine, coastal and shelf science* **134**:98-107.

Davlasheridze, M., M. Davlasheridze, K. Atoba, K. Atoba, S. Brody, S. Brody, W. Highfield, W. Highfield, W. Merrell, W. Merrell, B. Ebersole, B. Ebersole, A. Purdue, A. Purdue, R. Gilmer, and R. Gilmer. 2019. Economic impacts of storm surge and the cost-benefit analysis of a coastal spine as the surge mitigation strategy in Houston-Galveston area in the USA. *Mitigation and adaptation strategies for global change* **24**:329-354.

Deign, J. 2020. Carbon capture: Silver bullet or mirage? **2021**:*Green tech media*.

del Valle, A., M. Eriksson, O. A. Ishizawa, and J. J. Miranda. 2020. Mangroves protect coastal economic activity from hurricanes. *Proceedings of the National Academy of Sciences of the United States of America* **117**:265-270.

Dontis, E. E., K. R. Radabaugh, A. R. Chappel, C. E. Russo, and R. P. Moyer. 2020. Carbon storage increases with site age as created salt marshes transition to mangrove forests in Tampa Bay, Florida (USA). *Estuaries and coasts* **43**:1470-1488.

Doughty, C. L., J. A. Langley, W. S. Walker, I. C. Feller, R. Schaub, and S. K. Chapman. 2016. Mangrove range expansion rapidly increases coastal wetland carbon storage. *Estuaries and coasts* **39**:385-396.

Environmental Protection Agency. 2002. A framework for the economic assessment of ecological benefits. :1-168.

Fabiano, J. 2021. What is the saffir-simpson hurricane wind scale? **2021**:*Accuweather*.

Feher, L. C., M. J. Osland, G. H. Anderson, W. C. Vervaeke, K. W. Krauss, K. R. T. Whelan, K. M. Balentine, G. Tiling-Range, T. J. Smith III, and D. R. Cahoon. 2020. The long-term effects of Hurricanes Wilma and Irma on soil elevation change in Everglades mangrove forests. *Ecosystems* **23**:917-931.

Frohlich, T. C. 2018. From elena to katrina: These are the costliest hurricanes to ever hit the US. **2021**:*USA today*.

Galveston District's Hydrology and Hydraulics Branch. 2019. Attachment 3 climate change and sea-level rise effects for the hsc ecip feasibility study. :*U.S. Army Corp of Engineers*.

Gerbode, C. 2016. From hwy 6 to galena park a map of your neighborhoods nearest dangerous chemical facilities. :*Swamplot*.

Gillen, J. 2015. Erosion data. **2021**:*Beachpedia*.

Guannel, G., K. Arkema, P. Ruggiero, and G. Verutes. 2016. The power of three: Coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. *PLoS ONE* **11**:1-22.

Hanley, M. E., T. J. Bouma, and H. L. Mossman. 2020. The gathering storm: Optimizing management of coastal ecosystems in the face of a climate-driven threat. *Annals of botany* **125**:197-212.

Hassan, M. M., K. Ash, J. Abedin, B. K. Paul, and J. Southworth. 2020. A quantitative framework for Analyzing spatial dynamics of flood events: A case study of super cyclone Amphan. *Remote Sensing* **12**:Art. No.: 3454.

Hattab, T., F. Ben Rais Lasram, C. Albouy, C. Sammari, M. S. Romdhane, P. Cury, F. Leprieur, and F. Le Loc'h. 2013. The use of a predictive habitat model and a fuzzy logic approach for marine management and planning. *PLOS ONE* **8**:e76430.

Harris County Flood Control District. 2021. Flooded from the beginning. **2021**: *Harris County Flood Control District*.

Hengeveld, R. 1988. Mechanisms of biological invasions. *Journal of Biogeography* **15**:819-828.

Houston Galveston Area Council. 2015. Demographic and socio-economic changes in houston-galveston region A comparison of major metropolitan areas in the U.S. **2021**: *Houston Galveston Area Council*.

Hiatt, D., K. Serbesoff-king, D. D. Lieurance, D. R. Gordon, and S. L. Flory. 2019. Allocation of invasive plant management expenditures for conservation: Lessons from Florida, USA. *Conservation science and practice* **1**:7.1-10

Horstman, E. M., C. M. Dohmen-Janssen, P. M. F. Narra, van den Berg, N. J. F., M. Siemerink, and Hulscher, S. J. M. H. 2014. Wave attenuation in mangroves: A quantitative approach to field observations. *Coastal engineering* **94**:47-62.

Hudson, T., K. Keating, and A. Pettit. 2015. Cost estimation for coastal protection - summary of evidence. :*Environmental agency*.

Hutchison, J., M. D. Spalding, and Zu Ermgassen, Philine S E. 2014. The role of mangroves in fisheries enhancement marine and coastal biogeography view project native oyster restoration alliance (NORA). :*Native oyster restoration alliance*.

Jones, H. P., B. Nickel, T. Srebotnjak, W. Turner, M. Gonzalez-Roglich, E. Zavaleta, and D. G. Hole. 2020. Global hotspots for coastal ecosystem-based adaptation. *PLoS ONE* **15**:Art. No.: e0233005.

Kelleway, J. J., K. Cavanaugh, K. Rogers, I. C. Feller, E. Ens, C. Doughty, and N. Saintilan. 2017. Review of the ecosystem service implications of mangrove encroachment into salt marshes. *Global Change Biology* **23**:3967-3983.

Kida, M., and N. Fujitake. 2020. Organic carbon stabilization mechanisms in mangrove soils: A review. *Forests* **11**:Art. No.: 981.

Knutson, T. R., J. J. Sirutis, Zhao Ming, R. E. Tuleya, M. Bender, G. A. Vecchi, G. Villarini, and D. Chavas. 2015. Global projections of intense tropical cyclone activity for the late Twenty-first century from dynamical downscaling of CMIP5/RCP4.5 Scenarios. *Journal of climate* **28**:7203-7224.

Krauss, K. W., and M. J. Osland. 2020. Tropical cyclones and the organization of mangrove forests: A review. *Annals of botany* **125**:213-234.

LaRue, J., E. Campirano, R. Guenther, L. Kelley, M. Mierzwa, and J. Stastny. 2016. Overview of texas ports and waterways senate select committee on texas ports. Texas Department of Transportation :*Texas department of transportation*.

Lester, S. E., A. K. Dubel, G. Hernán, J. McHenry, and A. Rassweiler. 2020. Spatial Planning Principles for Marine Ecosystem Restoration. *Frontiers in marine science* **7**:Art. No.: 328.

Lingala, V. 2021. 2040 regional transportation plan . **2021**:*Houston Galveston area council*.

Lucey, R. 2020. Where to fish all over galveston island . :*Galveston guide*.

Mafi-Gholami, D., A. Jaafari, E. K. Zenner, A. Nouri Kamari, and D. Tien Bui. 2020. Spatial modeling of exposure of mangrove ecosystems to multiple environmental hazards. *Science of the total environment* **740**:Art. No.: 140167.

Marshall, A. R. 2017. Non-native and invasive species. **2021**:*U.S. fish and wildlife service*.

McKee, K. L. 2011. Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems. *Estuarine, coastal and shelf science* **91**:475-483.

McKee, K. L., and W. C. Vervaeke. 2018. Will fluctuations in salt marsh–mangrove dominance alter vulnerability of a subtropical wetland to sea-level rise? *Global change biology* **24**:1224-1238.

McLaughlin, R., T. Ruppert, and R. Edwards. 2018. Living with sea level rise on the upper texas coast. *Houston endowment*.

McNally, C. G., E. Uchida, and A. J. Gold. 2011. The effect of a protected area on the tradeoffs between short-run and long-run benefits from mangrove ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **108**:13945-13950.

Mohd Fauzi, N. F., T. H. Min, and A. M. Hashim. 2020. Assessment of Mangrove Replanting Site at Kg Tanjung Kepah, Lekir, Perak. *IOP Conference Series: Earth and Environmental Science* **549**:Art. No.: 012054.

Narayan, S., C. Thomas, J. Matthewman, C. C. Shepard, L. Geselbracht, K. Nzerem, and M. W. Beck. 2019. Valuing the flood risk reduction benefits of florida's mangroves. Nature Conservancy. *Nature conservancy*.

National Oceanic Atmospheric Association. 2008. The gulf of mexico at a glance. :*NOAA*.

National Park Service. 2019. Coastal engineering - hard structures. **2021**:*NPS*.

Octavio Aburto-Oropeza, Exequiel Ezcurra, Gustavo Danemann, Víctor Valdez, Jason Murray, and Enric Sala. 2008. Mangroves in the Gulf of California Increase Fishery Yields. *Proceedings of the National Academy of Sciences - PNAS* **105**:10456-10459.

Osland, M. J., N. Enwright, R. H. Day, and T. W. Doyle. 2013. Winter climate change and coastal wetland foundation species: salt marshes vs. mangrove forests in the southeastern United States. *Global change biology* **19**:1482-1494.

Osland, M. J., R. H. Day, C. T. Hall, L. C. Feher, A. R. Armitage, J. Cebrian, K. H. Dunton, A. R. Hughes, D. A. Kaplan, A. K. Langston, A. Macy, C. A. Weaver, G. H. Anderson, K. Cummins, I. C. Feller, and C. M. Snyder. 2020. Temperature thresholds for black mangrove (Avicennia germinans) freeze damage, mortality and recovery in North America: Refining tipping points for range expansion in a warming climate. *Journal of ecology* **108**:654-665.

Patrick, C. J., L. Yeager, A. R. Armitage, F. Carvallo, V. M. Congdon, K. H. Dunton, M. Fisher, A. K. Hardison, J. D. Hogan, J. Hosen, X. Hu, B. Kiel Reese, S. Kinard, J. S. Kominoski, X. Lin, Z. Liu, P. A. Montagna, S. C. Pennings, L. Walker, C. A. Weaver, and M. Wetz. 2020. A System Level Analysis of coastal ecosystem responses to hurricane impacts. *Estuaries and coasts* **43**:943-959.

Perry, C. L., and I. A. Mendelssohn. 2009. Ecosystem effects of expanding populations of Avicennia germinans in a Louisiana salt marsh. *Wetlands* **29**:396-406.

Radabaugh, K. R., R. P. Moyer, A. R. Chappel, E. E. Dontis, C. E. Russo, K. M. Joyse, M. W. Bownik, A. H. Goeckner, and N. S. Khan. 2020. Mangrove Damage, Delayed Mortality, and Early Recovery following Hurricane Irma at two landfall sites in Southwest Florida, USA. *Estuaries and coasts* **43**:1104-1118.

Randall, K. 2013. Swept away: Beach erosion continues to be huge problem for texas. **2021**:*Texas A&M today*.

Ravens, T. M., R. C. Thomas, K. A. Roberts, and H. Santschi Peter. 2009. Causes of Salt Marsh Erosion in Galveston Bay, Texas. *Journal of coastal research* **25**:265-272.

Reja, M. Y., S. D. Brody, W. E. Highfield, and G. D. Newman. 2017. Hurricane recovery and ecological resilience: Measuring the impacts of wetland alteration post Hurricane Ike on the Upper TX Coast. *Environmental management* **60**:1116-1126.

Roth, D. 2012. Texas hurricane history demonstrates need to prepare for upcoming season. Federal Information & News Dispatch, LLC. *Lanham*.

Rozas, L. P., P. Caldwell, and T. J. Minello. 2005. The Fishery Value of Salt Marsh Restoration Projects. *Journal of Coastal Research* :37-50.

Saintilan, N., N. C. Wilson, K. Rogers, A. Rajkaran, and K. W. Krauss. 2014. Mangrove expansion and salt marsh decline at mangrove poleward limits. *Global Change Biology* **20**:147-157.

Schaper, D. 2017. 3 reasons houston was A "sitting duck" for harvey flooding. **2021**:*National public radio*.

Scheffel, W. A., K. L. Heck Jr., and M. W. Johnson. 2018. Tropicalization of the Northern Gulf of Mexico: Impacts of salt marsh transition to black mangrove dominance on faunal communities. *Estuaries and coasts* **41**:1193-1205.

Shaftel, H., D. Bailey, R. Jackson, and S. Callery. 2021. The effects of climate change. **2021**:*NASA*.

Siverd, C. G., S. C. Hagen, M. V. Bilskie, D. H. Braud, and R. R. Twilley. 2020. Quantifying storm surge and risk reduction costs: a case study for Lafitte, Louisiana. *Climatic change* **161**:201-223.

Smith, C. Galveston bay: A brief history of one of america's great waters . courtesy of Galveston Bay Foundation. 8 Houston History **10**:2.

Stevens, P. W., S. L. Fox, and C. L. Montague. 2006. The interplay between mangroves and saltmarshes at the transition between temperate and subtropical climate in Florida. *Wetlands Ecology and management* **14**:435-444.

Sullivan, C. R., A. R. Smyth, C. W. Martin, and L. K. Reynolds. 2021. How does mangrove expansion affect structure and function of adjacent seagrass meadows? *Estuaries and coasts* **44**:453-467.

Texas Agriculture and Mining University of Galveston. 2010. Galveston bay facts. :*TAMUG*.

Thakur, S., I. Mondal, P. B. Ghosh, P. Das, and T. K. De. 2020. A review of the application of multispectral remote sensing in the study of mangrove ecosystems with special emphasis on image processing techniques. *Spatial information research* **28**:39-51.

Thorhaug, A. L., H. M. Poulos, J. López-Portillo, J. Barr, A. L. Lara-Domínguez, T. C. Ku, and G. P. Berlyn. 2019. Gulf of Mexico estuarine blue carbon stock, extent and flux: Mangroves, marshes, and seagrasses: A North American hotspot. *Science of the total environment* **653**:1253-1261.

Tidwell, M. 2006. Exporting calamity: Katrinas for everyone: Coming soon to a coast near you. *World watch* **19**:43-45.

Tuniski, A., Verhagen, H. J. The use of mangroves in coastal protection. *Proceedings of the Coastal Engineering Conference*; 2014.

University Corporation for Atmospheric Research. 2021. Hurricane damage. **2021**: *University Corporation for Atmospheric Research*.

University of Houston.org. 2021. Natural disaster risk in houston. **2021**:*UH.org*.

Van Coppenolle, R., and S. Temmerman. 2020. Identifying ecosystem surface areas available for nature-based flood risk mitigation in coastal cities around the world. *Estuaries and coasts* **43**:1335-1344.

Vanderklift, M. A., C. Doropoulos, D. Gorman, I. Leal, A. J. P. Minne, J. Statton, A. D. L. Steven, and T. Wernberg. 2020. Using propagules to restore coastal marine ecosystems. *Frontiers in marine science* **7**:Art. No.: 724.

Walton, M. E. M., G. P. B. Samonte-Tan, J. H. Primavera, G. Edwards-Jones, and L. Le Vay. 2006. Are mangroves worth replanting? The direct economic benefits of a community-based reforestation project. *Environmental conservation* **33**:335-343.

Woodroffe, C. D., K. Rogers, K. L. McKee, C. E. Lovelock, I. A. Mendelssohn, and N. Saintilan. 2016. Mangrove sedimentation and response to relative sea-level rise. *Annual review of marine science* **8**:243-266.

Yoskowitz, D. W. 2009. Gulf of mexico origin, waters, and biota: Volume 2, ocean and coastal economy. Pages 21-28 *In* Cato, J. C., editor. The productive value of the gulf of mexico, *Texas A&M University Press, College Station*.

Zaveri, M. 2020. Galveston bay report card 2020. Galvbaygrade.org :*Hearst communications inc.*.

Zhang, Y., Y. Yang, K. Yang, X. Tan, X. Sun, B. Leng, C. Zhou, and B. Zhu. 2020. Non-linear wave attenuation quantification model improves the estimation of wave attenuation efficiency of mangroves. *Estuarine, coastal and shelf science* **245**:Art. No.: 106927.