Ecosystem Services of Mangrove Forests and How Climate Change May Impact the Indian River Lagoon

MS Technical Paper

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Introduction

Mangroves are a taxonomic group that refers to halophytic subtropical and tropical trees and shrubs; at least fifty species exist around the world. Three species of mangrove dominate the Florida coastline extending southward from the Ponce de Leon Inlet in Northeast Florida and from Cedar Key in Western Florida; specific species include red, black, and white mangrove (Lewis et al., 1985). Mangroves greatly influence the environmental and economic health of coastal communities in Florida. One of the beneficial ecosystem services provided by mangrove forests is shoreline protection against physical erosion due to wave action, high winds, and flooding created by storms and hurricanes; the intricate root systems stabilize sediments (see **Figure 1**) and decrease wave energy to preserve the integrity and structure of the coastline and upland habitats. The root systems also help preserve water quality by filtering pollutants and water clarity by trapping suspended sediments. Mangrove communities also provide ecologically and economically valuable submarine nursery and feeding grounds for shrimp, oysters, clams, crabs, sea turtles, manatee, dolphin, and many species of fishes, including sharks, tarpon, jack, sheepshead, red drum, and snapper. Above ground, mangrove swamps are equally as valuable and provide nesting and feeding habitat for wading birds such as the roseate spoonbill, great egret, and white ibis. Predatory mammals such as the Florida panther, raccoon, river otter, and bobcat also greatly rely on mangrove systems. Mangrove systems also play an important role in regulation of both local and global climate through carbon sequestration.

Despite the numerous valuable goods and services provided by mangrove communities in the state of Florida, their well-being is continuously threatened; urban development on and around the coast is the leading cause of mangrove deforestation. Dredging, filling, and diking are methods used to control and reshape mangrove communities to better suit human needs at the time. This may include construction of roads, buildings, bridges, or canals and mosquito control structures. Additionally, urban development upland can result in runoff carrying herbicides, fertilizers, and sundry other contaminants into the system. Oil spills can also cause vast amounts of damage to mangroves by coating roots and causing fish kills (Lewis et al., 1985). Mangroves also face additional danger from climate change-induced sea level rise, which will make these ecosystems even more vulnerable to these threats. It is difficult to determine how exactly individual mangrove stands will respond to changing sea levels, but according to Wongthong (2008), when sediment accretion rates equal or exceed rates of sea level rise, it is expected that mangroves will retreat landward, if no barrier to movement and growth exists (see **Figure 2**). However, when rates of sea level rise outpace accretion rates, mangrove forests will flood and no longer be viable. (Wongthong, 2008).

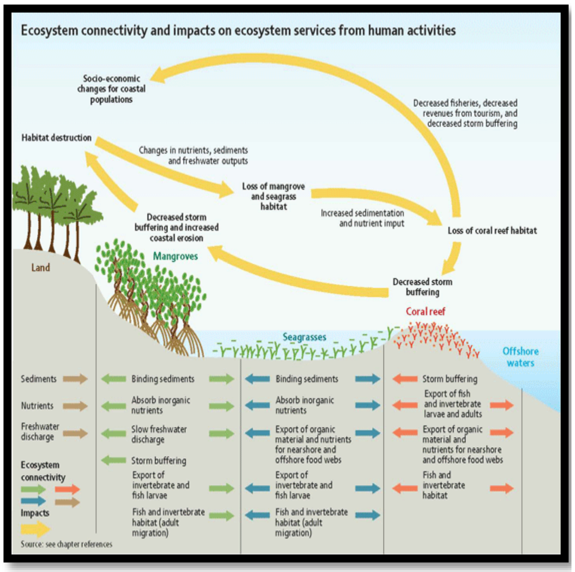

Figure 1. Impacts, benefits and interconnectivity of mangrove habitats (Mehlhaff, 2013)

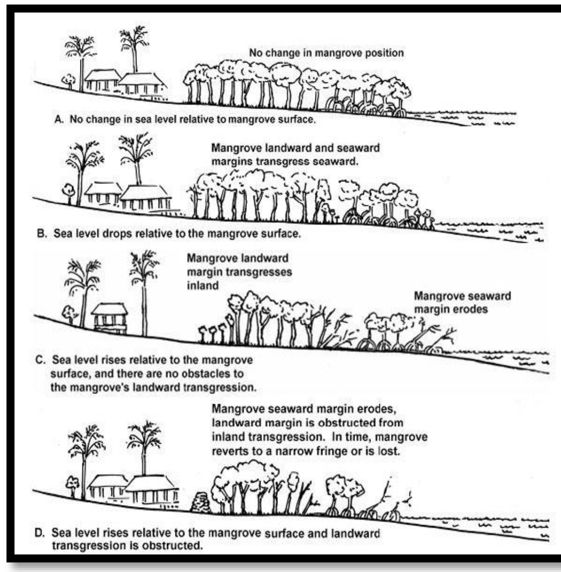

Figure 2. Response of mangrove systems to changing sea levels (Wongthong, 2008)

These issues and more present themselves copiously within the Indian River Lagoon, a 156-mile stretch of Floridian coastline extending from the Ponce de Leon Inlet to the southern boundary of Martin County. Despite a long history of dredging, ditching, and impounding and current algal bloom and water quality issues, there has been a monumental surge in protection projects within the lagoon because stakeholders and officials are beginning to recognize the plethora of services provided by healthy marsh systems (SJRWMD, 2013). Unfortunately, rising sea levels may present an additional obstacle in mangrove rehabilitation and health. The latter half of this paper will address the vulnerability of mangroves in the Indian River Lagoon, using my own personal maps and metrics.

Mangrove Services

Shoreline Stabilization

Mangrove forests act as a natural buffer against high wind and wave energy, protecting the shoreline and upland communities that lie behind. There is a wealth of observational evidence to support their preservation benefits; calm lagoons are often the immediate result of a mangrove-dominated coastline and coastal communities protected by mangroves are often less affected by hurricanes, cyclones, and tsunamis (Wells et al., 2005). This is particularly evident in Southeast Asia where large expanses of mangrove forest have been converted to shrimp farms; the villages surrounded by shrimp farms rather than mangroves experienced increased damage and human mortality in a powerful 1999 cyclone (Mangrove Action Project, 2005). Mangroves are powerful wave attenuators; wave energy and size may dissipate by 75 percent per 300 meters when waves pass through their thick, tangled root systems (Wells et al., 2005). Dissipation potential is determined by several factors (Hashim et al., 2013)

1) Density: a dense mangrove forest is more effective at wave height reduction and energy dissipation than a less dense forest due to the increased incidence of friction and drag force,
2) Band width: according to Lacambra et al. (2008), the optimal mangrove width for wave attenuation is between 100 and 1500 meters; however, this can vary with mangrove species, density, and hydraulic conditions. A tall, dense forest will require a narrower band to achieve the same shoreline protection capabilities as short, sparse forest,
3) Forest structure: stem stiffness, presence of pneumatophores, wide roots and branches, vegetation, and intricate stem configurations increase bed roughness and drag force to decrease wind, wave, and tidal forces,

4) Age: age can be used as a proxy for mangrove size, trunk and root diameter, and stem density; older, and therefore, bigger, mangroves provide greater shoreline protection and wave attenuation,
5) Height: according to Lacambra et al. (2008), taller trees are more vulnerable to wind damage, but seem to be more resistant to wave energy,
6) Water depth and wave height: maximum wave height is proportional to water depth to bed surface (in shallow waters); sandy, un-vegetated beds are less adept at wave height reduction, while beds with mangrove vegetation obstruct water flow and are better able to decrease wave height

Mangroves further stabilize shorelines through sediment accretion. The complex root structures of mangrove trees trap sediment, especially in estuarine systems fed by large rivers. Additionally, due to the low energy environments created by mangrove forests, larger sediments settle quickly out of the water column, if the system remains relatively undisturbed, smaller clay-sized particles may also settle (Phillips et al., 2017). It is also important to note the feedback loop created when mangrove shorelines are eroded or lost; as the intertidal zone is eroded, there exists less protection against erosion, leading to increased erosion rates, which leads to less protection, and so on.

Carbon Storage

Mangroves sequester massive amounts of carbon and store it as aboveground biomass; on average, mangrove forests store about 152 tons/hectare (Hutchinson et al., 2013). However, there is massive variability in aboveground mangrove biomass, and therefore carbon sequestration capabilities, around the globe (see **Figure 3**); some of the most productive areas are in Indonesia, New Guinea, Borneo, and Columbia (Hutchinson et al., 2013). Unfortunately, these are also some of the areas experiencing the most mangrove loss; globally, nearly a third of all mangrove biomass has been converted to urban or agricultural uses (Hutchinson et al., 2013). Donato et al. (2011) estimate that mangrove loss may account for 10 percent of the total carbon emissions from overall deforestation.

Most mangroves also produce peat soil, which is extremely carbon-rich. Peat production is commonly associated with methane emissions, which is an even more effective greenhouse gas than carbon dioxide; however, in the case of mangrove peat production, the saline soils typically dampen this methane productivity (Spalding, 2013). The carbon fixing and storing capabilities of mangrove forests make them a major player in the fate of the global climate.

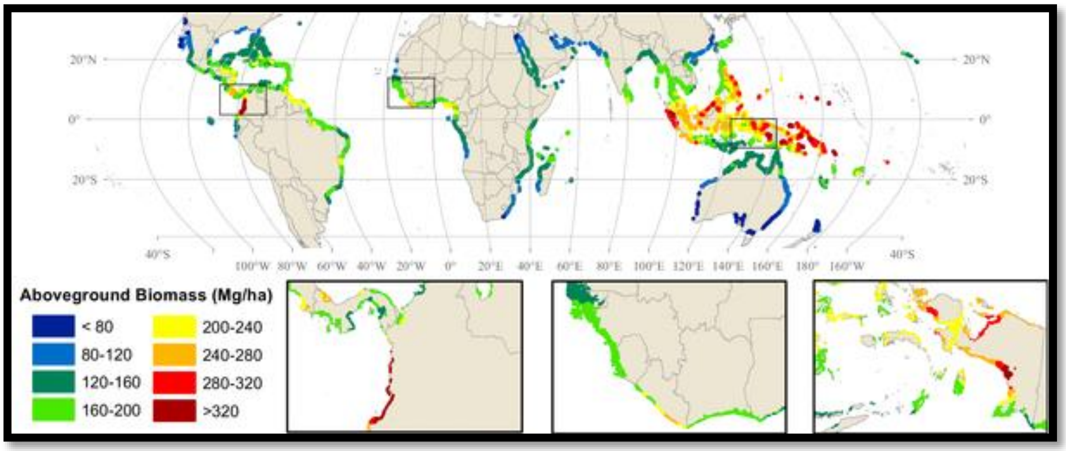

Figure 3. Map depicting global distribution and modeled aboveground biomass per unit area of mangroves (Hutchinson et al., 2013)

Microclimates

In addition to reducing global emissions of climate-warming carbon, mangroves also affect their surrounding microclimates. According to a study regarding the relationship between mangrove canopy cover and microclimate, the presence of mangroves has effects on air temperature and relative humidity, rainfall, and wind.

1) Temperature and relative humidity: mangrove cover has a dampening effect on maximum air temperatures and daily temperature ranges; less solar radiation reaches the air and soil beneath the mangrove canopy resulting in less heating and lower temperatures. The canopy also retains moisture at higher rates than unvegetated areas causing higher relative humidity values,
2) Rainfall: mangrove density, leaf shape, and root/branch architecture increase rainfall interception and result in rainwater pooling in catchment areas; the amount of rainfall reaching the soil determines the overall salinity and can control the species that occupy the area,

3) Wind: within the mangrove canopy, wind speed measurements are decreased by about 70 to 85 percent due to intensity-diminishing effects of vegetation (see **Figure 4**)

(Lima and Galvani, 2013)

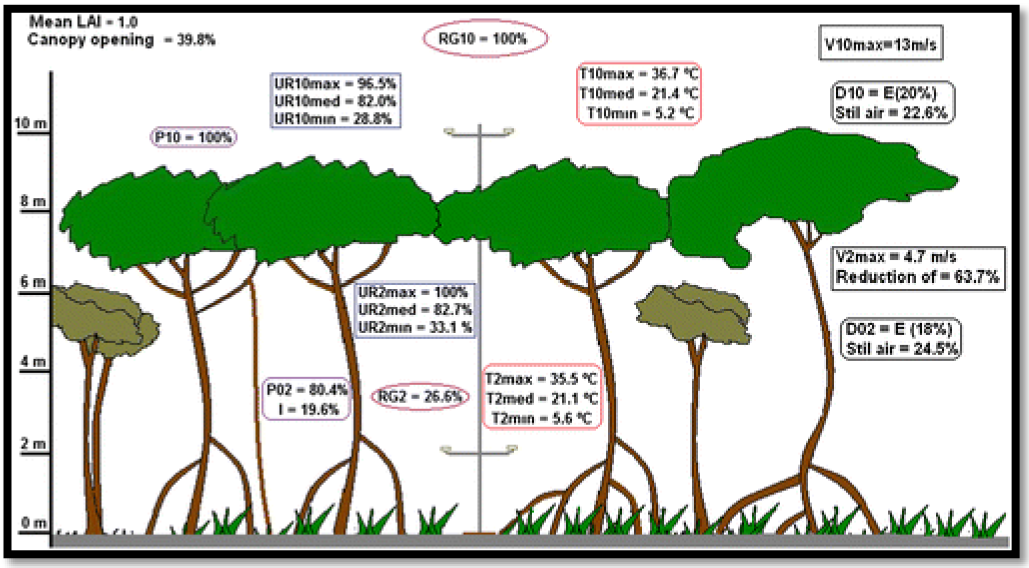

Figure 4. Study of canopy cover effect on precipitation (P), relative humidity (UR), solar radiation (RG), maximum gust speed (V), predominant wind direction (D), and temperature (T) at 2 meters (2) and 10 meters (10) above the soil surface. Barra do Ribeira, Iguape, Sao Paulo, Brazil (Lima and Galvani, 2013).

Water Quality

Mangroves are able to preserve water quality and clarity by absorbing pollutants and settling sediments out of the water column. Heavy metals, nutrients, and suspended particles are filtered in the shallow-water zones, preventing them from reaching open-water environments (Wells et al., 2005). The presence of anaerobic conditions in the intertidal zone where mangroves thrive results in in high soil redoxomorphic potential. These conditions foster denitrification and, depending on the hydroperiod and presence of pneumatophores or roots, may influence the redox potential for of sulfur, magnesium, and iron (Ewel et al., 1998). Additional processes that serve to immobilize pollutants include “adsorption to ion exchange sites, binding to organic matter, precipitation into insoluble compounds, and incorporation into lattice structures” (Tam and Wong, 1999).

The sorption of heavy metals, such as Cd, Cr, and Cu, however, is dependent on salinity, which varies with tidal period and freshwater inputs (Tam and Wong, 1999). The treatment and precipitation capabilities of mangrove marshes have implications beyond the natural environment; mangroves are able to regulate their own ecosystems against pollution inputs to a certain extent and may be further useful to humans through the implementation of cheap and readily available wastewater treatment.

Products

In addition to the valuable ecosystem services mangrove forest provide, they also afford a disproportionally large number of useful and profitable goods; the most obvious of these products are fish and shellfish, but also included are medicines, timber, and honey (Wells et al., 2005).

Fisheries

The productivity of mangrove ecosystems has been linked to the well-being of valuable fisheries because of the role mangroves play as nursery habitat for a variety of marine and estuarine species (Carrasquilla-Henao and Juanes, 2017). These species often shift habitats throughout their lifetimes and shift to open-ocean or coral reefs; however, the time spent within the mangrove is essential for their survival. It is hypothesized that mangroves serve as such productive nurseries due to the high availability of food and the protection provided from both predators and physical disturbances; decreased predation is a result of increased turbidity and decreased visibility and the habitat complexity created by roots and pneumatophores (Carrasquilla-Henao and Juanes, 2017). Several factors influence species richness within a mangrove community (Alongi, 2002):

1) Large estuaries have large species ranges (large estuary: 104-197 species; small estuary: 8-128 species)
2) Most Atlantic estuaries are less diverse than those of the Indo-Pacific
3) Tropical estuaries are more diverse than subtropical estuaries
4) Species composition is influenced by connectivity between mangroves and adjacent habitats

The health and diversity of mangrove ecosystems is essential to fishery yields; a study in Florida found that crustacean and juvenile fish catches were an order of magnitude greater where a healthy mangrove stand was present, as opposed to where there were no mangroves present (Robertson and Duke, 1987). A similar study regarding two estuaries in Queensland, Australia showed that the fish yields were significantly more abundant within areas where mangroves were present than where they were absent (Robertson and Duke, 1987).

The economic benefit of the habitat provided by mangroves is enormous; catches vary across the globe from large commercial fisheries to local subsistence harvest. Seafood caught from mangroves may have an average global value of up to $170,000 per square kilometer (Wells et al., 2005). Juvenile brown, pink, and white shrimp are one of the most important commercial species found in mangrove ecosystems; the estimated value of the 2000 to 2004 shrimp harvest in the United States is estimated at $2.5 billion (Lellis-Dibble et al., 2008). The red drum is an important fish species in both commercial fisheries and recreational harvest; the commercial value of red drum in the United States between 2000 and 2004 is estimated at $936,475 (Lellis-Dibble et al., 2008). Other profitable species include blue crab, oysters, and clams (Pendleton, 2008).

Forestry

A few mangrove species provide commercial timber that is used for making newsprint and matches; additionally, the tannins are used to preserve wood and fishing nets, as well as to dye cloth (Wells et al., 2005). In Florida, it has become profitable to use mangroves pollen as a source for honey production in coastal communities where deforestation has removed many other sources (Wells et al., 2005). Mangrove timber is also used as building material, fuel, and animal fodder, particularly in developing third world coastal communities where it may be difficult to come by alternatives. The timber is used in home, boat, and jetty construction because it is particularly resistant to water rot; the wood is used as firewood and charcoal in homes and engines because of its high caloric value; and the leaves are used as feed for cattle and goats (Wells et al., 2005). While timber can be an important resource provided by mangrove forests, it is important to harvest sustainably to maintain other equally valuable ecosystem services.

Pharmaceuticals

Mangrove products are used in traditional medicines where hospitals and modern medicines are not available or not affordable; the bark of certain species can be used to treat diarrhea, cholera, and dysentery (see **Figure 5**) (Bhat and Sivakumar, 2014). Recently, metabolites, steroids, saponins, tannins, and other extracts derived from mangroves have become of interest to the pharmaceutical industry (Bandaranayake, 1998). Saponins have long been recognized for their use as natural detergent; spermicidal, molluscicidal, antimicrobial, and anti-inflammatory properties have also been identified (Bandaranayake, 1998). Tannins present in food and beverages have been linked to disease prevention due to their antibacterial properties, which provide protection from invading parasites and microbes (Bandaranayake, 1998). Additionally, anti-HIV, antiviral, anti-inflammatory, and anticancer compounds have been identified from mangrove species; much of the vast mangrove forests of the world, however, remain undiscovered, along with their untold medicinal uses and healing properties.

Acanthus illicifolius and A. ebracteatus	leaf juice used as hair preserver, fruit pulp as blood purifier, dressing for boils and snake bite, Leaf preparation used for rheumatism
Aegiceras corniculatum and A. floridium	bark and seed used as fish poison
Ceriops tagal	source of firewood and tannins, yields high quality dyes, bark stops hemorrhaging (source of anticoagulant)
Derris trifoliata	used to kill fish
Excoecaria agallocha	fish and arrowhead poison in Thailand skin it is known to cause blindness and eruptions in the Philippines it is used medication for toothache, in Malaysia bark extract is taken as a purgative
Rhizophora species	timber, fishing stakes, piles, firewood, charcoal, and tannins;
R. mucronata	Bark used to treat diarrhea, dysentery, and leprosy; fruit sap used as a mosquito repellent; wine is made from fruit and Honey from the nectar.
Sonneratia caseolaris	fruit is eatable, sap is used as a skin cosmetic, leaves are used for goat Food.
Sonneratia ovate	fruit is eatable and used to treat sprains fermented juice used as anticoagulant
Xylocarpus species	firewood, timber, and tannin; bark Extract is used to treat cholera.

Figure 5. Uses of several of the many mangrove species from around the world (Bhat and Sivakumar, 2014)

Case Study: Indian River Lagoon

Background

The Indian River Lagoon (IRL) is a 156-mile long estuary that runs along Florida's east coast, spanning from the Ponce de Leon Inlet in Volusia County southward through Martin County (SJRWMD, 2013). The lagoon system is made up of three separate lagoons, Mosquito Lagoon in the north, the Banana River in Brevard County, and the Indian River Lagoon proper. The IRL is an incredibly ecologically important system; it has one of the largest bird populations in North America, almost a third of North America's manatee population permanently or transitionally lives within the lagoon, and the lagoon contains the northernmost extent of mangroves and the southernmost extent of salt grasses on the east coast (Dybas, 2002). Not only are the mangroves and marshlands within the IRL ecologically diverse and prolific, but they also contribute nearly $300 million in annual fishery revenues and provide invaluable water quality and sediment stabilization services (Dybas, 2002). Despite the benefits provided by mangroves in the IRL, there are many threats to the health and productivity of the ecosystem.

Issues

Habitat Alteration and Loss

Since the 1950s, the lagoon has been drained, diked, and ditched for the sake of mosquito control and urban development; nearly 85% of mangroves have been lost (US Fish and Wild Life Service). This alteration in hydrology has resulted in the loss of key functions, biodiversity, and habitat (Dybas, 2002). Efforts are being made, however, to restore and reconnect these impaired salt marshes; the northern portion of the IRL, Mosquito Lagoon, has had the most success in recent years where nearly 60% of the previously impounded wetlands have been restored (Brockmeyer et al., 1996).

Pollution

A growing population in the IRL watershed has resulted in an increase in wastewater and stormwater releases into the lagoon from point source outflows as well as from surface runoff (SJRWMD, 2013). These flows carry heavy metal pollutants and nutrients, in the form of organic waste or fertilizers, which result in algal blooms and eutrophication throughout the lagoon. Outfalls from Lake Okeechobee have been associated with "super" algal blooms such as the one in 2011, which resulted in seagrass, fish, and manatee die offs (SJRWMD, 2013).

Sea Level Rise (SLR)

In addition to the stressors currently facing the IRL, climate change and rising sea levels will further threaten the system; if accretion rates are unable to keep up with sea level rise rates, many of the mangrove communities will be lost. Additionally, a changing climate will also affect water salinity, temperature, and dissolved oxygen content and have adverse impacts on seagrasses, fish, and marine invertebrates (Dineen, 2014).

Vulnerability of IRL Mangroves to SLR (GIS Work)

Objectives

The overarching purpose of this project was to utilize the Geographic Information System ArcGIS to determine the level of vulnerability of mangroves to sea level rise in the Indian River Lagoon. This was achieved with the following objectives:

i. Describe the effects of changing sea levels on mangrove viability
ii. Determine a qualitative threshold to measure varying levels of impact from sea level rise
iii. Determine which areas within the lagoon will be most impacted
iv. Discuss the importance of these findings

Significance

It is well accepted, in scientific literature, that the globe is undergoing a period of sea level rise that will continue well into the future. In 2012, the National Oceanic and Atmospheric Association (NOAA) published *Global Sea Level Rise Scenarios for the United States National Climate Assessment*; this report projects low, intermediate, and high sea level scenarios up to the year 2100. Rising sea levels will affect a great many aspects of modern topography, geography, and hydrology, including mangrove distribution and health.

The benefits of mangroves to coastal communities have been thoroughly defined and represented in **Figure 1** and throughout this paper. For these reasons, it is important that we protect our mangrove ecosystems; this study will help identify which systems that will be most susceptible to sea level rise. Studies like this could help make decisions that would protect and fortify our coasts in the face of climate change and sea level rise.

Criteria Selection

There are myriad factors affecting mangrove tolerance to sea level rise, the most obvious of those being the amount of rise; this study however, will focus on the geographic and geologic properties that will affect the vulnerability of individual parcels of mangrove forests within the Indian River Lagoon. Three of the most important factors that determine mangrove resilience are the species type, geologic setting, and proximity to developed uplands (McLeod and Salm, 2006).

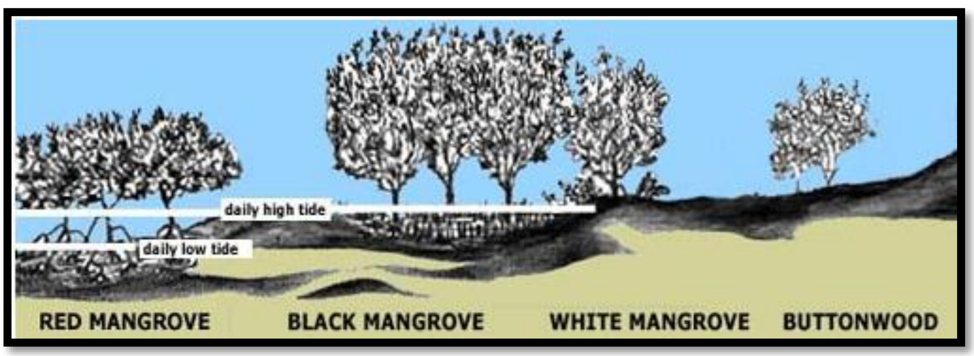

Figure 6. Mangrove species zonation (Florida Museum of Natural History).

In a 2003 study by Ning et al., it was found that black mangroves have a higher tolerance for persistently inundated soils, indicating that black mangroves have a higher chance of survival than red or white mangroves with rising sea levels. This is because black mangroves have developed root-like protrusions called pneumatophores (see **Figure 6** and note pneumatophores) that allow oxygen exchange even under inundated conditions (Lewis et al., 1985). The distribution of mangrove species can be seen in **Figure 7,** which was created specifically for this paper.

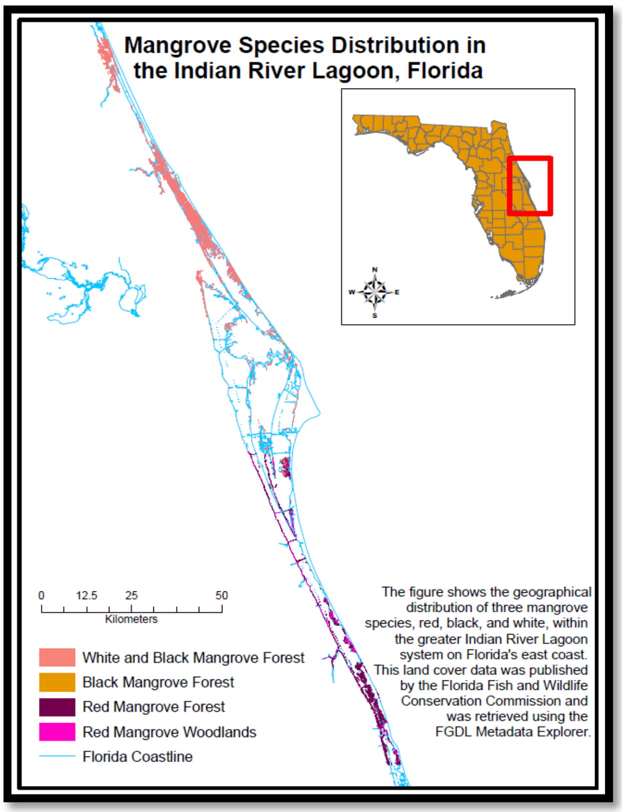

Figure 7. Distribution of mangroves in the IRL.

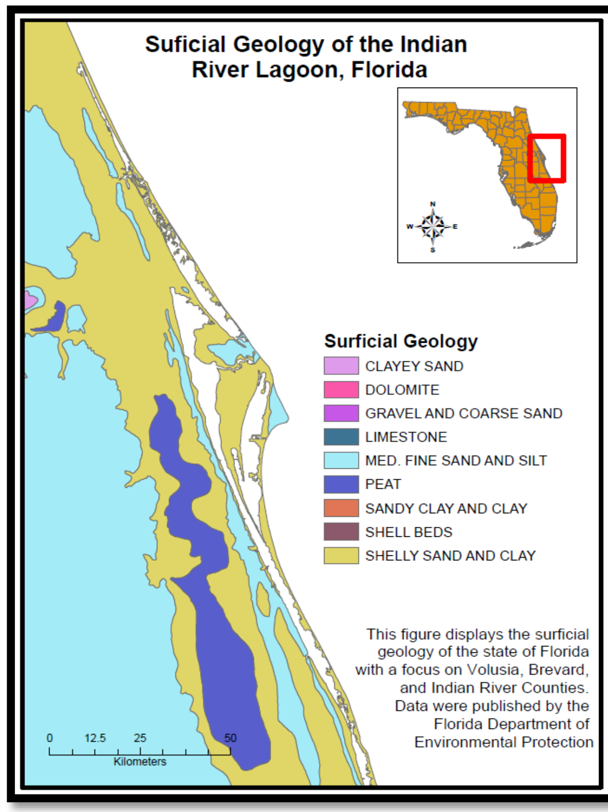

Figure 8. Geologic setting of the study area.

In addition to mangrove species, geologic setting can greatly affect mangrove persistence in the face of sea level rise. Those forests with little terrestrial inputs or siliciclastic sediments and clay minerals will likely be unable to outpace or even keep up with rising sea levels. This indicates that, geologically, mangroves will be most vulnerable in a carbonate setting, which includes environments dominated by limestone, dolomite, or shell deposits (McLeod and Salm, 2006). The geology of Florida consists mostly of carbonates and some overlying sands and clays (geologic setting displayed in **Figure**

8).The last criterion that was in this study is the feasibility of upland progression. That is to say, are there any physical barriers to mangrove movement inland as sea levels rise? If the area upland of mangroves is heavily urbanized and developed, it does not allow the forest to compensate for lost seaward habitat and it will be more vulnerable to rise. Much of the lower Indian River Lagoon is heavily developed, but there is still agricultural, rangeland, wetlands, and forested areas that may be utilized by mangroves as sea levels rise.

Vulnerability	Local Conditions	Explanation
Most Vulnerable	Low relief islands	- low rates of sediment and peat accretion, particularly vulnerable to sea-level rise because they are subject to drought and wave erosion - expected to experience increased flooding, inundation and salinization of soils and freshwater (Shea et al. 2001).
	Lack of rivers	- lack of sediment and freshwater
	Carbonate settings	- often associated with atolls and islands, where landward migration to escape sea-level rise may not be possible - sediments are mostly locally derived
	Areas subsiding due to tectonic movements, groundwater extraction, or underground mining	- will experience higher sea-level rise and inundation
	Micro-tidal sediment starved environments (small Caribbean islands) (Ellison 1993)	- lack of sediment will lead to decreased geographic distribution and species diversity of mangroves (Houghton et al. 2001)
	Mangroves blocked by coastal development or steep topography	- unable to move inland when sea level rises
Least Vulnerable	Mangroves in deep sediment on high islands	- structurally stronger than mangroves in shallow sediment on low islands (Gillison 1980) and less vulnerable to storm surges than low islands (UNEP 1994) - high islands will be better adapted to survive predicted climate changes due to their larger surface areas, freshwater availability, better soils, and more diverse resources (Shea et al. 2001).
	Riverine mangroves	- receive large amounts of sediment from other areas (Woodroffe and Grindrod 1991) - most productive mangrove habitats due to high nutrient concentrations associated with sediment trapping (Ewel et al. 1998).
	Macro-tidal sediment rich environments (mangroves in northern Australia)	- access to sediment and strong tidal currents to redistribute sediment (Woodroffe and Grindrod 1991)
	Mangroves with room to move landward (backed by low-lying areas, salt flats, undeveloped areas)	- have the opportunity to expand inland when sea level rises
	Mangroves in remote areas	- have limited anthropogenic stresses and not blocked by coastal communities from moving landward
	Mangroves surrounded by flourishing dense mangrove forests	- have steady supply of propagules and seeds

Figure 9. Factors affecting mangrove vulnerability to sea level rise (McLeod and Salm, 2006.

Of course, there are many more factors that may influence mangrove susceptibility and resilience, some of which are explored in **Figure 9**. However, based on the dynamics discussed above, I determined that the mangrove forests that would be most vulnerable to sea level rise would be those that are predominantly made of red and white species, had carbonate based surface geology (limestone, dolomite, shell fragments), and were bordered within 100-meters by developed land, including the land use categories of "Urban and Built-up," "Special Classifications," and "Transportation, Communications, and Utilities." Parcels that meet all of these criteria are displayed in bright green; parcels that exhibit at least one of these criteria are shown in a darker shade; and parcels that do not meet any are displayed in the darkest green.

Results

Using the criteria enumerated above, about 99% of the Indian River Lagoon's mangrove can be considered at least intermediately vulnerable to sea level rise and about 26% may be considered highly vulnerable; only 1% of the current mangrove stand within the lagoon has low vulnerability (using the criteria of this study). Any parcel with a surface geology consisting of carbonate/shelly sediments and a dominant stand of red mangroves and developed land (including urban, transport, and specialized) within 100 meters of the center was considered highly vulnerable. An intermediately vulnerable parcel needed only fit one of the above criteria. A low vulnerability parcel would have a surface geology of mainly clay sediments, a dominant stand of black mangroves, and only forests, wetlands, agriculture, rangeland, or barren land classification uses within 100 meters. The results may be viewed in **Figure 10**.

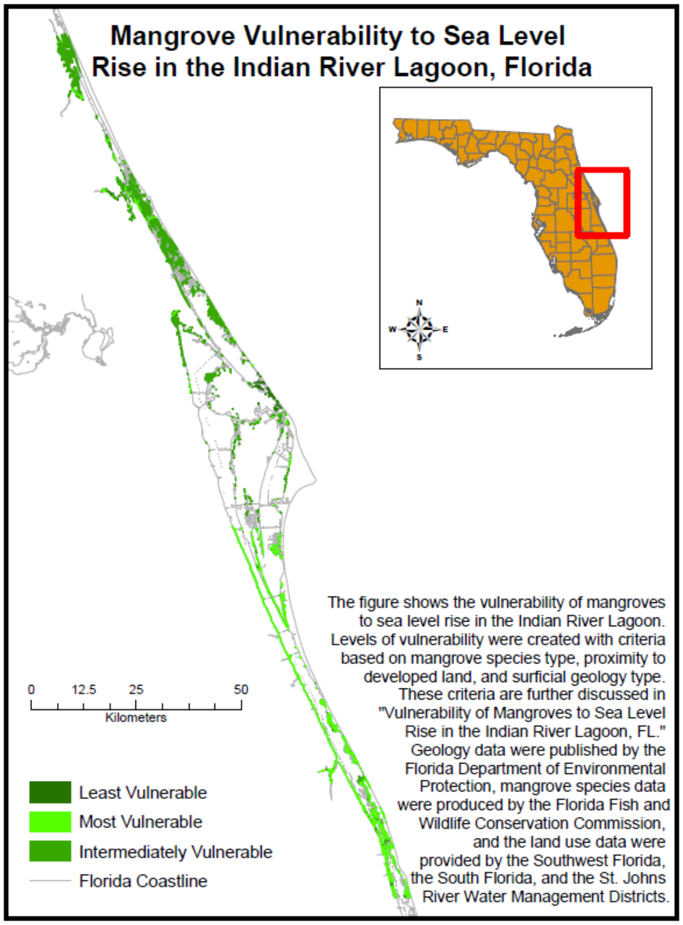

Figure 10. Vulnerability of mangrove communities within the IRL.

Discussion

This type of study is extremely important in the fight against sea level rise because it identifies problem areas that will need intervention if they are expected to continue to thrive. Continued research, data collection, and GIS analyses will allow scientist to better understand how mangroves (and our coastlines) will be affected by sea level rise and will therefore be able to influence policy and conservation efforts where success is most likely. A more detailed study should include bathymetric data, quantitative accretion rates, well-defined projections of sea level rise, and should account for human intervention and ingenuity.

Conclusions

Mangroves are exceedingly valuable for their coastline stabilization abilities, water quality and clarity benefits, provision of habitat to economically profitable and ecologically important species, carbon sequestration services, and climate regulation capabilities. These benefits of mangrove communities are evident within the Indian River Lagoon system, despite the many stressors they are faced with. Due to their economic and ecologic importance within the lagoon, it is important to look to the future of these systems in the face of climate change so that policy makers may act quickly to preserve and protect our ecosystems.

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