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Sea Level Rise Vulnerability Analysis of Mangrove Ecosystems Using GIS

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HALMOS COLLEGE OF NATURAL SCIENCES AND OCEANOGRAPHY

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By

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Table of Contents

1. List of Figures

2. List of Tables

3. Abstract

Climate change is accelerating beyond what is natural due to excessive emissions from human activities. The sea level has been rising for many years and is currently at a rate of 3.6 mm/yr. Mangroves are known to only keep pace with a sea level rate of less than 1.2 mm/yr. Mangroves are particularly vulnerable to rising sea levels if they are not able to keep pace through vertical sediment accretion or inland migration. To test the vulnerability of the south Florida mangrove ecosystems to sea level rise, this study analyzed changes in the mangrove forest coverage of the Oleta River State Park over a period of 56 years. An analysis of Oleta was chosen to be representative of a South Florida mangrove ecosystem due to its accessibility. The mangrove population within Oleta River State Park, residing in an area with low sedimentation rates and anthropogenic constraints on the landward side, is at risk due to sea level rise. An ArcGIS analysis of archival aerial imagery from specific years available was undertaken to determine mangrove area and the cause of change. The analysis found a fluctuation in mangrove area over the past 50 years due to human development and mangrove regrowth. Ultimately there was a 42% decrease and a total loss of 3.0 km^2 in mangrove area between 1961 and 2017. Field surveys discovered many stressors experienced by the mangroves, including pollution, invasive species and sea level rise. The results suggest that while the majority of change in area of the ecosystems was due to development, nonetheless, 11% of change was due to Australian pine growth and 2% due to shoreline loss. These results support the need for effective management plans to conserve these important ecosystems.

Keywords: Mangrove, remote sensing, ArcGIS, climate change, wetlands, sea level rise

4. Introduction

4.1 Study Region: Oleta River State Park

4.1.1 Importance of This Study at Oleta River State Park

Oleta River State Park (Oleta) is a Florida State Park within Dade County, located in the City of North Miami (Figure 1) (Blatt, 2018). This area was acquired in 1980 (Division of Recreation and Parks, 2008) and established in 1986; it is the largest urban state park in Florida with a total area of 422 hectares (Blatt, 2018). According to the Oleta River State Park Unit Management Plan, the Oleta mangrove habitat is the largest remaining tidal swamp along Biscayne Bay north of MacArthur Causeway (Division of Recreation and Parks, 2008). The mangroves and river produce important habitat areas for many different species and is considered the largest and most important native and wildlife habitat within the City (Blatt, 2018).

Oleta is valuable to the City of North Miami, providing approximately $46 million in annual revenue and supporting 749 jobs in the Fiscal Year 2016-2017 (Blatt, 2018). Monthly visitation to Oleta is equivalent to more than the entire population of the City (Blatt, 2018) with annual visitation reaching half a million in the Fiscal Year 2016-2017 (Cutshaw, 2017). Recreation services include kayaking, canoeing, biking trails, fishing, camping and hiking (Blatt, 2018; Division of Recreation and Parks, 2008). Oleta has a 365 m long beach which serves as the only public beach within the City (Blatt, 2018). Sandspur Island, also within Oleta's boundaries, has an area of 8 hectares and is located less than a half kilometer south of Oleta's mainland (Blatt, 2018). It is a popular site for kayakers and boaters (Blatt, 2018). Oleta provides ecosystem services to humans by 1) serving as a natural storage area for flood waters, 2) reducing flooding, and 3) recharging groundwater (Lodge, 2016).

The mangrove community is a crucial component of the park's natural ecosystem, and its continued presence into the future is concerning. The habitats within Oleta are subject to numerous stressors including invasive species, urban runoff, sewage spills, and toxic pollutants from marinas and the adjacent Munisport Landfill (Division of Recreation and Parks, 2008). In spite of these threats, Oleta has not been classified as an Area of Critical State Concern (as defined in section 380.05, Florida Statues) or even considered for this designation (Division of Recreation and Parks, 2008).

Oleta River State Park Vicinity Map

Figure 1: Vicinity of Oleta River State Park.

The City of North Miami has designated “The Oleta State Recreation Area and Mangrove Preserve” as Environmentally Sensitive Land ("Natural Storage Areas," n.d.). Management of the park is in collaboration between the Florida Park Service and the Biscayne Bay Aquatic Preserve (Division of Recreation and Parks, 2008). Currently, the management plan for the park does not include provisions for rising sea levels (Division of Recreation and Parks, 2008).

The goal of this study is to determine whether mangrove habitat is likely to be inundated by sea level rise. Predicting the effects of rising sea levels will provide useful insight for managing these natural communities as our environment changes (Peyronnin et al., 2013). Accurate predictions can provide sufficient lead time to minimize and offset anticipated loss (Gilman, Ellison, Duke, & Field, 2008). Results from this study can be used to advise the next management plan in their efforts to preserve and protect these mangroves and the continued presence of the Oleta as a whole. If it is true that the mangrove habitat is threatened by sea level rise, then specific management plans are required.

4.1.2 Statement of Purpose

Rising sea level, an existential threat to Oleta and other coastal parks, is currently not included in the park management plan. The goal of this project is to assess whether, and to what extent, the mangrove habitat at Oleta is threatened due to sea level rise. Threat assessment was accomplished by analyzing historic imagery analysis and field checking the mangrove habitats of Oleta. The results of this study provide a clear picture of the change in the mangroves over recent history and indicate that rising sea level has already impacted this area. These data were used to assess the resiliency of this habitat to change by analyzing current stressors on this area. This information could be used by Oleta management planners to help mitigate the effects of rising sea level on these mangrove habitats.

4.1.3 History.

Oleta, located at the north extent of Biscayne Bay, is within a shallow limestone depression (Lodge, 2016). Lodge describes the Biscayne Bay as a historically narrow, isolated lagoon. According to Lodge, sea level rose high enough to invade the lagoon 5,500 years ago, transitioning it into estuarine and marine waters of the modern system by 3,200 years ago.

Prior to 1925, the natural ecosystem consisted of a large band of mangroves bordering a freshwater marl prairie (Harlem, 1979; Teas, Wanless, & Chardon, 1976). This area had historically been low lying between 0 and +0.3 m mean sea level, MSL (Division of Recreation and Parks, 2008). Only a small (less than 0.4 hectare) zone resided above the intertidal zone, representing small hammock islands scattered throughout the park area, at about 1.5 m above MSL (Division of Recreation and Parks, 2008). A low salinity of approximately 4 parts per thousand (ppt) (Division of Recreation and Parks, 2008) was maintained by freshwater input via diffuse flows through wetlands, tidal creeks, springs, and groundwater seepage (Lodge, 2016). Oleta is considered a historic outflow zone for the Everglades prior to anthropogenic impacts within the past century (Division of Recreation and Parks, 2008).

The mangrove habitat that would become Oleta has been altered significantly over the past century (Division of Recreation and Parks, 2008; Lodge, 2016). Mangroves were restricted to the edges of Biscayne Bay prior to anthropogenic hydrological alteration of the Haulover inlet in the early 1900s (Lodge, 2016). Biscayne Bay transitioned from a tidal estuary to the modern-day marine lagoon due to a large decrease in freshwater input as a result of the flood control on the Everglades (Lodge, 2016) through the Swamp and Overflowed Lands Grant Act (Division of Recreation and Parks, 2008). The alteration to the natural hydrology allowed mangroves to encroach on freshwater marl prairie communities (Division of Recreation and Parks, 2008). Dense bands of red, black and white mangroves proliferated over the following half century, despite the creation of numerous shallow ditches for mosquito control in 1935 through 1956 (Division of Recreation and Parks, 2008).

The mangrove habitat was reduced by approximately half due to dredging and filling for development of the Interama project between 1962 and 1964 (Division of Recreation and Parks, 2008). This project was a failed attempt to build a large-scale trade and cultural center called the InterAmerican Cultural and Trade Center, referred to as “Interama” (Blatt, 2018; Lejeune, 2010). While Interama was never completed, the project left the park with 3 to 6 m wide canals at 0 to -1.5 m below MSL, an open water lagoon, and elevated uplands at about 1.5 m above MSL, some reaching up to 6 m above MSL (Division of Recreation and Parks, 2008).

4.1.4 Present condition Biscayne Bay and Oleta.

Oleta resides within south Florida at the north end of Biscayne Bay (Figure 1). Water depth in the bay is generally shallow, with the center being 2-3.4 m deep at low tide (Lodge,

2016). Tides are semidiurnal with an amplitude of slightly over 0.6 m, measured at Virginia Key (Lodge, 2016). Salinity varies greatly due to management by the South Florida Water Management District on the upstream canal, fluctuating between 7 and 34 ppt with an average of 25 ppt (Division of Recreation and Parks, 2008).

Freshwater enters the bay through point source discharge (Lodge, 2016). The Snake Creek Canal (Figure 2) north of Oleta, flows into northern Biscayne Bay (Lodge, 2016). Thirteen canals discharge into the modern-day Biscayne Bay (Lodge, 2016). Freshwater from the canals leads to stratification and prevents freshwater input to benthic communities that was provided in the past by historic groundwater seepage (Lodge, 2016). Land acquired for the Interama project now is divided between Oleta, Florida International University's Biscayne Bay Campus, and the delisted Munisport Superfund site that is now Sole Mia, a housing development and shopping plaza (Figure 2) (Blatt, 2018).

Figure 2: The Boundaries of Oleta River State Park ((Division of Recreation and Parks, 2008).

4.1.4.1 Sediments.

Sands here are composed of silica (from the Appalachian Mountains) and locally limestone composed of derived shell material (Lodge, 2016). The Natural Resources Conservation Service identified five different soil types within the park region (Figure 3) (Division of Recreation and Parks, 2008; Noble, Drew, & Slabaugh, 1996).

- Tidal Terra Ceia muck is in the mangrove forest along the Biscayne Bay, Oleta River and an isolated triangular shaped mangrove area. Tidal Terra Ceia is a poorly drained organic soil common in tidal swamps and marshes.
- Tidal Pennsuco marl soil occurs at the eastern fringes of the park. This marl soil is thin, approximately 12 cm.
- Another marl origin soil, Tidal Perrine marl occurs in the northwest portion of the park. Both areas are characterized by expanses of exotic vegetation. This is unusual because the natural vegetation of these two soil types are typically scattered and stunted red mangroves.

4.1.4.2 Significant Species Present in Oleta River State Park.

There are both riverine and fringe forest mangrove communities found at the park, along with several small isolated mangrove areas “Estuarine Tidal Swamp” (Figure 4) (Division of Recreation and Parks, 2008). The wide riverine forest lining the Oleta River, has an elevation between 0 and +1.5 m MSL, consisting mainly of tall red mangroves (*Rhisophora mangle*) 8 to 15 m in height, along with less frequently occurring white mangroves (*Laguncularia racemosa*) (Division of Recreation and Parks, 2008). Red and white mangroves seedlings populate the understory (Division of Recreation and Parks, 2008). These mangroves were established after the 1925 Haulover Cut and 1945 aerial photographs show that a dense line of small mangroves was already established (Division of Recreation and Parks, 2008). Since the 1970s, red mangroves have fallen over along the shoreline, likely due to boat wake activity and boring isopods (Teas et al., 1976).

Marine species found within Biscayne Bay include soft corals, sponges and species of small hard corals along the deeper hard limestone bedrock substrate (Lodge, 2016). Marine vegetation includes turtle grass and manatee grass, both abundant along the shallow benthic

habitat made from marine algae produced carbonate mud (marl) and sandy sediment substrates (Division of Recreation and Parks, 2008; Lodge, 2016).

The elevated uplands have been populated by invasive vegetation including Australian pine *Casuarina equisetifolia*, (Division of Recreation and Parks, 2008). Australian pine, imported to Florida in 1887 is a prevalent invasive species within Oleta (Lodge, 2016). The pines invade disturbed areas then shade out and smother herbaceous plants with leaf litter (Lodge, 2016). Australian pine is damaging in beach dune areas as well, because roots can obstruct turtle and crocodile nesting on low energy narrow beaches (Lodge, 2016), such as the 365 m stretch of public beach found in Oleta.

Oleta is a low-lying coastal area (Division of Recreation and Parks, 2008). As sea level changes and mangrove species intolerant of new conditions perish, more resilient species may colonize the area (Kirwan, Temmerman, Skeehan, Guntenspergen, & Fagherazzi, 2016; Schuerch et al., 2018). Faster colonizers may dominate areas newly opened by sea level rise (Lovelock, Bennion, Grinham, & Cahoon, 2011). A shift in mangrove composition and distribution can only occur with enough time to recolonize and landward space in which to do so (Kirwan et al., 2016; Schuerch et al., 2018).

Natural Communities Map

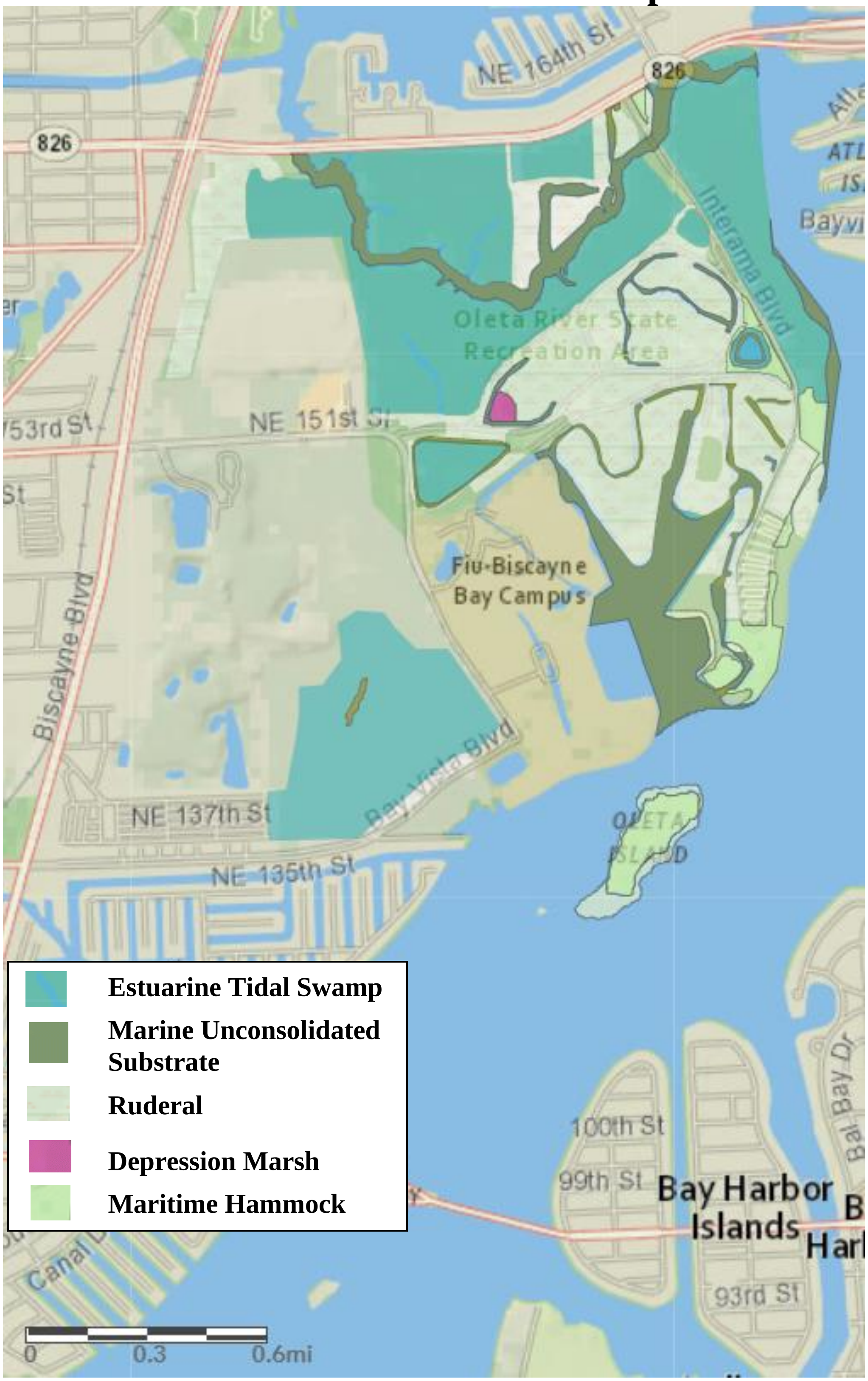

Figure 3: Natural Communities Map

4.2 Mangrove Ecology

The following information on mangrove ecology is largely summarized by two sources, "The Everglades Handbook, Fourth Edition" by Lodge (2016) and "Life Along the Mangrove Shore" by Marsh & Bane (1995). Lodge (2016) defines mangrove forests as habitats comprised mostly of mangrove trees located at the interface between terrestrial and marine systems. In South Florida, mangrove forests evolved through a 3,000-year period of slowly rising sea levels at a rate of 0.3 mm/yr, which created an accumulated coastal deposit of sand, marl, shell and mangrove peat. The tidal nature of this environment subjects the mangrove trees to a great deal of environmental stress, including periods of flooding, abruptly varying salinities (mostly due to rainfall and evaporation), and temperature swings. Mangrove trees are specially adapted to live in saline waters and anaerobic soils with high methane and hydrogen sulfide levels. Flora and fauna in a mangrove forest need to be able to persist in a variety of conditions (Lodge, 2016).

Mangroves are found in tropical ecosystems around the world (Lodge, 2016). Ellison and Stoddart (1991) found that mangroves reside mostly within the intertidal zone, mainly +/- 1 m between mean sea level and the level of mean high-water spring tides. In Tongatapu, Tonga modern mangroves occur between 0.4 and 0.9 m above MSL, with mean tidal range of 1.07 m (Ellison & Stoddart, 1991).

4.2.1 Mangrove species in Florida.

Within Florida, there are three mangrove species: *Rhizophora mangal* (red mangrove), *Aviccennia germinans* (black mangrove) and *Laguncularia racemose* (white mangrove) (Lodge, 2016).

The red mangrove occurs at the most exposed, high wave action areas, typically at the most seaward extend of the forest (Lodge, 2016). As described by Marsh and Bane (1995), red mangroves in southern Florida as typically less than 6 m tall. Red mangroves are characterized by 8-15 cm long leaves which are leathery, and elliptical shaped. This mangrove produces pale yellow flowers, 2.5 cm in diameter, from stalks at the base of the leaves. Seedlings begin as conical brown fruits, which germinate on the tree (Marsh & Bane, 1995).

Red mangroves do not require saltwater to thrive but do possess unique adaptations to life in a saline environment. Lodge (2016) notes that aerial "prop" roots originate high up on the trunk, sometimes even from branches, and extend downward towards the sea and soil beneath.

This serves to provide additional support, securing the trees, especially important in resistance to hurricanes and high wave action. Further, Lodge notes that mangrove habitats have anaerobic hydric soils from being continuously submerged with no atmospheric oxygen exposure To deal with this, red mangroves have lenticels, small holes on the prop roots, which are used to exchange gases with the atmosphere and supply the roots with oxygen. This also allows the red mangrove to persist in the interior of a mangrove forest, as well, where conditions are increasingly anaerobic. Excess salt is excluded from entering the tree at the roots. The roots also serve an important ecological function below the surface by providing a secure substrate for numerous sessile epifauna, such as barnacles, sponges, mussels and oysters (Marsh & Bane, 1995).

Red mangroves, unlike most other plants, are unable to re-sprout from branches and trunks after the tree is damaged (Lodge, 2016). Other plants sprout from dormant buds under the bark beneath growing branches when a branch breaks off (Lodge, 2016). Red mangroves can initially produce dormant buds; however, damaged mangroves die within a few years because older branches do not have the ability to sprout new branches (Lodge, 2016). This is a vulnerability of the red mangrove in that it easily dies off when damaged (Lodge, 2016).

Black mangroves, like red mangroves, are also adapted to hydric soils but have different adaptive features (Lodge, 2016). Their roots generate from beneath the soil and emerge as upward extensions beyond the surface, called pneumatophores, up to 0.3 m above the soil. This can lock in water and increase flooding duration in areas where these pneumatophores are very dense. Black mangrove salt-balance system differs from other Florida mangrove species because they have an internal system that excretes excess salt through glands in their leaves, rather than exclusion at the roots (Lodge, 2016). Black mangroves are also identified by their blunt tipped leaves, 5-15 cm long, with a dark green surface and lighter undersurface, often spotted with salt crystals (Marsh & Bane, 1995). The bark of the black mangrove is dark brown to black in color and divided into small rectangular shapes (Marsh & Bane, 1995). Small white flowers emerge in clusters at the tips of short twigs (Marsh & Bane, 1995). The fruits are lima-bean shaped, conical and compressed, 2.5 cm+ in diameter (Marsh & Bane, 1995). Black mangroves are the most tolerant of cold weather (Lodge, 2016), which is useful in extreme weather situations, often seen with increasing effects of climate change.

White mangroves grow anywhere throughout a mangrove forest, provided the shoreline is protected (Lodge, 2016). They are, however, found most often in upland areas at the landward extension of the forest (Lodge, 2016). There are two gland-like openings, petioles, where the leaf stem meets the leaf (Lodge, 2016). When under stress, white mangroves form pneumatophores as well as prop roots, albeit to a lesser extent than the black or red mangroves, respectively (Lodge, 2016). They have thick leaves that are blunt and rounded with a notch at the apex and colored dull light green on both sides (Marsh & Bane, 1995). Their fruits begin as white flowers on spikes at the end of branches and later turn into small teardrop shaped fruits with a leathery texture (Marsh & Bane, 1995).

Mangroves disperse through floating seeds, which settle in an adjacent area (Lodge, 2016). Red mangrove has a special seed dispersal through specially adapted propagule seeds (Lodge, 2016). These grow while still on the tree and form the trunk of the seedling (Lodge, 2016). A propagule can drop straight from the parent tree and grow where it lands in very shallow waters (Lodge, 2016). If the propagule lands in deeper water, it will float for several days before its buoyancy is altered and it floats for an additional several weeks before sinking and growing roots if the location is shallow with low wave energy (Lodge, 2016).

4.2.2 Soil building.

Mangroves facilitate soil building in two major ways: as mangroves die, matter from their leaves, trunk, and stems decays and becomes mangrove peat; also, mangrove roots naturally trap sediments such as sand, shells, and marl from coastal waters and materials carried in by storm tides (Lodge, 2016; Moffett, Nardin, Silvestri, Wang, & Temmerman, 2015). The accumulation of mangrove pollen (peat) in the upper half of the tidal range is a useful sea level indicator (Engelhart, Horton, Roberts, Bryant, & Corbett, 2007). Tongatapu and Grand Cayman Mangal stratigraphic analysis shows a peat accumulation rate of 0.8-0.9 mm/yr without coastal sediment input (Ellison and Stoddart, 1991)

Lodge (2016) describes that the composition of mangrove soils includes the above described mangrove peat and trapped sediments, as well as dissolved substances in seawater. Lodge notes that methane (CH_4) is produced through peat decay. Sulfate (SO_4), abundant in seawater, is converted to hydrogen sulfide (H_2S) via sulfate-reducing bacteria and is responsible for the characteristic rotten egg smell of mangrove forests (Lodge, 2016). Hydrogen sulfide,

toxic to most plants, is tolerated by mangrove species through their root-aeration adaptations (Lodge, 2016).

It is important to note the difference between soil building and land building (Lodge, 2016). Often mistaken to be land builders, mangroves are soil builders. Lodge notes that land building only occurs though an unusual event where a large storm or hurricane deposits enough material to raise the mangrove swamp above high tide and this process usually causes mangrove mortality, as described by Ellison (1999) (as cited in Moffett et al., 2015). Soil building occurs through the process of accumulating mangrove peat (leaves, stems, branches), sand, shells and other sediments (Lodge, 2016). Erosion must be minimal for soil building to occur (Godoy & De Lacerda, 2015).

4.2.3 Erosion buffer.

Mangrove roots also provide coastal stabilization from erosion, buffering the land during periods of high wave energy and storms (Gilman et al., 2008; McKee, Cahoon, & Feller, 2007). Mangroves trap sediment and stabilize the substrate with roots (Moffett et al., 2015). By these processes, mangroves can aid in buffering against sea level rise (Temmerman et al., 2013; Costanza et al., 2008; Gedan et al., 2011; Moller et al., 2014; all as cited in Moffett et al., 2015).

4.2.4 Habitat provider.

Mangroves provide habitat for many organisms such as sponges, barnacles, crustaceans, fishes, manatees, birds, mollusks and bacteria (Alongi, 2008, 2015). They increase coastal water quality, biodiversity, and provide a nursery habitat for fishes and crustaceans (Gilman et al., 2008). Gilman et al., (2008) also found these functions benefit adjacent habitats.

The shallow, protected, and tidal habitat that is associated with mangroves in south Florida is well suited for the eastern oyster, also known as the American oyster, *Crassostrea virginica* (Lodge, 2016). In turn, the presence of these oysters, particularly when formed into oyster bars, are known to accelerate mangrove establishment, especially red mangroves (Lodge, 2016).

The mangrove trees themselves become nourishment for organisms through the decay of their leaves, stems, and pollen (Lodge, 2016). First the decaying material becomes food for larger marine life, broken down further, it becomes food for decomposing bacteria and fungi, becoming a protein rich detritus which looks like a slimy brown film on the leaf surface (Lodge,

2016; Marsh & Bane, 1995). The detritus is then available for use by organisms such as small crustaceans and fish, delivering energy to the base of the food web (Lodge, 2016). The benefits of mangroves are then felt throughout the ecosystem by providing a nursery habitat for juvenile animals (Lodge, 2016).

4.2.5 Importance to humans.

Mangrove forests provide many benefits for humans. Mangroves have a high economic importance, providing over $1.6 billion/year in ecosystem services worldwide (Polidoro et al., 2010). Wetland ecosystem services are valued up to $194,000 per hectare per year (Costanza, et al., 2014, as cited in Schuerch et al., 2018). Wetlands trap pollution and increase water quality (Teuchies, et al., 2013 as cited in Schuerch, et al. 2018). Mangrove restoration is economically beneficial, as seen in a study conducted by The Ramsar Convention Secretariat (2001), mangroves in Thailand cost $946 per hectare to restore but only $189 per hectare to protect. It is important to focus on preservation of current mangrove forests before they die off, because once wetlands are degraded, they are difficult to restore as suggested by high rates of failure in coastal wetland restorations (Palmer, 2008; Hughes & Paramor, 2004; Williams & Orr, 2002; Williams & Faber, 2001; all as cited in Moffett et al., 2015).

Consequences of mangrove loss include a reduction in biodiversity, nursery habitat, human resources (such as products and tourism), water quality, as well as negative effects on adjacent habitats (Ellison & Stoddart, 1991; Ewel, Twilley, & Ong, 1998; Mumby et al., 2004; Nagelkerken et al., 2008; Walters et al., 2008). Mangrove degradation eliminates a major resource for human communities that rely on mangrove products and services (Gilman et al., 2008). Given that mangroves are important erosion and storm buffers, providing protection from storm surges and flooding, loss in mangrove area results in the increase of threats to the shoreline and human safety (Gilman et al., 2008).

Greenhouses gases, such as carbon dioxide (CO_2), trap heat in the atmosphere and are responsible for the anthropogenically accelerated change in climate (IPCC, 2013; Kristensen, Bouillon, Dittmar, & Marchand, 2008). Mangroves are substantial sites for carbon storage (Donato et al., 2011). Accumulated organic carbon in mangroves, which is not degraded by microbes, becomes stored in sediments (Alongi, 2008). As such, mangroves are considered carbon sinks, an environment that absorbs carbon, through their high rates of primary production and carbon burial (Baur et al., 2013; Duarte et al., 2013; Pendleton et al., 2012; Mcleod et al.,

2011; all as cited in Moffett et al., 2015). Mangrove destruction would generate the release of a large quantity of stored carbon and further contribute to greenhouse gas emissions (Gilman et al., 2008).

4.3 Climate Change and Sea Level Rise

The climate is changing beyond what is natural due to excess greenhouse gas emissions released into the atmosphere due to human activities (IPCC, 2013). Sea levels are rising through thermal expansion of sea water and melting of glaciers, leading to increased coastal erosion, flooding, storm surges, salt-water intrusions and other damaging effects (Pachauri et al., 2014). These two conditions, melting of the polar ice caps and thermal expansion, are nearly equal contributors to sea level rise (Lodge, 2016). Precipitation patterns are changing, increasing runoff, which leads to eutrophication (algae blooms), increased frequency and severity of flooding and more intense storms/hurricanes (IPCC, 2013).

The rate of sea level rise worldwide is not consistent (IPCC, 2019). This is due to geologic instabilities, including glacial rebound, the process where melting glaciers lessen the downward force on the earth’s crust, allowing it to rebound and raise up with buoyancy; in contrast, areas with land subsidence will exhibit a greater than average sea level rise (IPCC, 2019). Land areas such as Florida that are free from the influence of glacial rebound or land subsidence provide the most reliable rates of sea level rise (Lodge, 2016).

The rate of sea level rise has increased over the past century (Pachauri et al., 2014). It is very likely that the rate of sea level rise between 1901 and 1990 was 1.4 mm/yr; and between 2006 and 2015 the rate increased 2.5 times to 3.6 mm/yr on average (Figure 5) (IPCC, 2019). Under the IPCC RCP8.5 scenario, the rate of sea level rise will be 15 mm/yr in 2100 (IPCC, 2019).

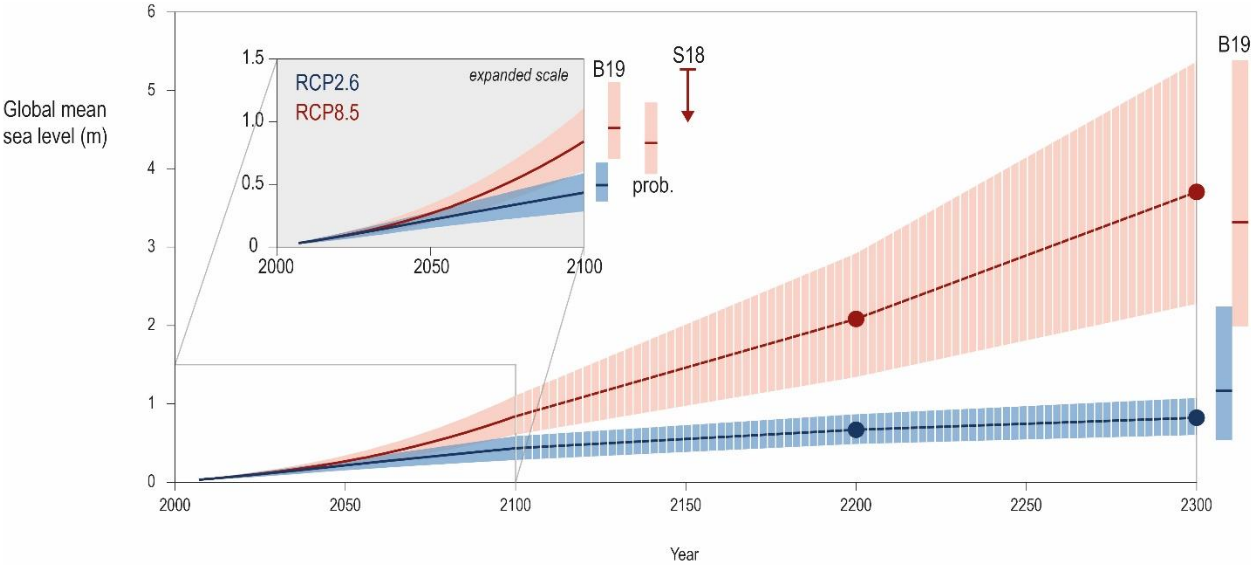

Figure 4: The 2019 IPCC projected sea level rise through 2300 (IPCC, 2019)

4.3.1 Mangroves and sea level rise.

There are multiple factors to consider when determining the ability of a mangrove population to persist in the face of rising seas. However, if the sea rises faster than the rate of surface sediment accretion, the mangroves cannot keep pace (Alongi, 2008; Gilman et al., 2008; Kirwan et al., 2016; Schuerch et al., 2018). Mangroves are threatened when there is no space available for landward migrations; this is exacerbated in low-lying areas (Gilman et al., 2008; Nicholls, Townend, Bradbury, Ramsbottom, & Day, 2013; Parkinson, DeLaune, & White, 1994).

The success of mangrove resilience to sea level rise depends upon the rate of sea level rise compared to sediment accumulation (Alongi, 2008; Cahoon et al., 2006; Doyle, Krauss, Conner, & From, 2010; Gilman, Ellison, & Coleman, 2007; Gilman et al., 2008). Sediment accumulation, erosion and resultant elevation changes affect a mangrove forest's ability to migrate during sea level rise (Godoy & De Lacerda, 2015). Mangroves are known to only be able to keep pace with a rate of less than 1.2 mm/yr sea level rise (Ellison and Stoddart, 1991) given that there is sufficient sediment input (Schuerch et al., 2018; Kirwan et al., 2016). Historically, soil accretion rates in mangrove forests coincide with sea level rise, allowing mangroves to migrate inland (Alongi, 2015). By contrast, climate is changing more rapidly than ever before (Pachauri et al., 2014). Traill et al. (2011) found that mangrove migration inland

kept pace with the rate of mangrove loss seaward under minimal sea level rise scenarios but could not keep pace under maximal sea level rise scenarios. For example, mangroves in subtropical Australia are projected to not be able to keep up with the accelerating rate of sea level rise (Traill et al., 2011).

In order to migrate inland there needs to be favorable conditions of the slope of the land, and available space (Gilman et al., 2008). In areas with low sediment input and high anthropogenic structure constraints, such as is found in the Caribbean Sea and the southerneastern US coast, there could be a loss of 66% of current wetland cover (Schuerch et al., 2018). Schuerch et al. (2018) found there to be a sediment deficiency of -20 to -5 mg l^{-1} surrounding Florida and the southern US east coast; this represents "the difference between the suspended sediment concentration needed for coastal wetlands to build up vertically with current (sea level rise) rates and the actual total suspended matter concentration derived from the satellite borne GlobColour data (http://globcolour.info)." The effect of increased sea level erosion of wetlands on the seaward side, while they are prevented from inland migration by infrastructure, is termed "coastal squeeze" (Torio & Chmura, 2013; Wolters et al., 2005; both as cited in Kirwan et al., 2016).

Since the severity of a disturbance to a habitat depends on its intensity and duration, the current anticipated pattern of sea level rise is a long-term severe disturbance that is projected to continue for the foreseeable future (Pachauri et al., 2014). Sea level rise will bring increased erosion rates and a greater frequency and intensity of storms (Ellison & Stoddart, 1991)**.** According to a study conducted by Ellison and Stoddart (1991), a sea level rise rate of 0.8-0.9 mm/yr is conducive for mangroves to keep pace; However, rates above 1.2 mm/yr will cause mangrove die off, given that sedimentation rates are low with no source of river input, as is the situation in southeast Florida. Low-lying areas and islands are particularly vulnerable (Ellison & Stoddart, 1991).

During rapidly rising sea level conditions, mangroves on the seaward side tend to dieback from sea level effects, such as erosion and weakening of root structures and falling trees, increased salinity and an excess in duration, frequency, and depth of inundation (Gilman et al., 2008). Sedimentation and ecological processes are altered (Ellison & Stoddart, 1991). The problem of rapidly rising sea levels on mangrove persistence is exacerbated through mangrove tree death, which leads to the root decomposition and land subsidence on the seaward

end (Lodge, 2016). This effect is increased through burrowing organisms, which dig into the soft decaying roots, such as burrowing shrimps (Lodge, 2016).

4.3.2 The use of remote sensing to study mangrove populations.

Remotely sensed imagery has been used in the past to analyze mangrove populations to detect changes over time (Kirui et al., 2013; Li, Meng, Ge, & Zhang, 2015; Sulong, Mohd-Lokman, Mohd-Tarmizi, & Ismail, 2002; Swetnam, Allen, & Betancourt, 1999; and many others). Indeed, aerial photographs provide valuable historical data, illustrating vegetative conditions, often spanning decades (Cohen, Behling, & Lara, 2005). Dahdouh-Guebas (2002) described in detail the application of remote sensing and geographic information systems (GIS) in retrospective as well as predictive studies on tropical coastal ecosystems, with an emphasis on mangroves. This enables early detection of impending environmental degradation to allow for appropriate mitigation measures to be taken (Cohen & Lara, 2003; Paine & Kiser, 2003). Additionally, remote sensing is essential in monitoring and mapping highly threatened mangrove ecosystems (Blasco, Aizpuru, & Gers, 2001; Kuenzer, Bluemel, Gebhardt, Quoc, & Dech, 2011). Remote sensing is the best option for long-term coastal vegetation monitoring, as opposed to field surveys alone (Moffett et al., 2015). In order to test for multiple stable states in coastal wetland systems, both spatially and temporally, extensive data at high resolution is required (Moffett et al., 2015).

Through comparison with local-scale field measurements, Schuerch et al. (2018) and Kirwan et al. (2016) concluded that most large-scale assessments overestimate the threat of sea level rise to coastal wetlands. Most projections of coastal wetland vulnerability to the impending sea level rise do not consider all essential factors, including geomorphological and socio-economic (Schuerch et al., 2018). Schuerch et al. (2018) found that previous studies overestimated the projected loss of mangroves regarding sea level rise. The results from the study by Kirwan et al., (2016) found the vulnerability of marshes also being overestimated through the failure to consider soil building processes and the potential for inland migration. It is the rate of sea level rise compared to the vertical sediment accretion rate as well as the ability for mangroves to migrate inland that determines success (Schuerch, et al. 2018). Taking the above two factors into consideration is the shortcoming of many studies (Schuerch, et al. 2018) and has been the main approach for over 30 years (Kirwan et al., 2016). These models are limited by not accounting for sediment accretion and the space available for inland migration

(Kirwan et al., 2016; Spencer et al., 2016). Most modeling is "bathtub" style that uses a static representation of the coast, without the landscape adjusting to sea level rise, leading to an inevitable drowning of the wetland over time (Kirwan et al., 2016). The Sea Level Affecting Marshes Model (SLAMM) is a more advanced model that accounts for the evolving landscape based on historical elevation change, it however does not simulate the dynamic feedbacks that allow wetlands to adapt to sea level rise with potential accelerated rates of sediment accretion or inland migration opportunities, and leads to drastic overestimations of wetland loss (Kirwan et al., 2016).

Schuerch et al., (2018) found that wetland area gains during sea level rise are possible and probable in certain areas. Their results suggest that the availability of accommodating space is the primary driving factor in determining wetland persistence during sea level rise. Coastal infrastructure is the main barrier to landward migration (Kirwan & Megonigal, 2013; Kirwan et al., 2016; Spencer et al., 2016). These human developments, such as buildings, roads, and railways, are expected to change over this century due to rising sea level (Schuerch et al., 2018). If wetland management plans are created to allow for this inland migration, large scale loss of wetland area is avoidable (Schuerch et al., 2018; Kirwan et al., 2016). Suggested by the models created by Schuerch, et al. (2018) and by Kirwan et al., (2016), the solution is to analyze the rate of accretion compared to the rate of sea level rise and to create a nature-based management plan to allow for accommodating space inland, possibly even lending to an increase in mangrove area. The process of providing accommodating space is less studied and more research should be done on this (Schuerch, et al. 2018). It is not only open space that is required, but also favorable soil conditions, therefore local coastal management strategies and engineering will be necessary (Schuerch, et al. 2018). The management solutions can include the displacement of flood defenses and designation of upland nature reserve buffers (Schuerch, et al. 2018).

4.3.3 Coastal zone management plans to prepare for climate change.

Coastal zone management presently focuses on the balance between human development, the natural communities, and protecting both against coastal hazards (Nicholls et al., 2013). The goal of coastal zone management is to increase resilience to change and long-term sustainability (Nicholls et al., 2013). When developing the management plan, it is useful to analyze historical imagery to determine trends and patterns of wetland loss in an area (Nicholls et al., 2013). The importance of stakeholder engagement through all processes is emphasized, as

well as the interconnectedness of all components (Nicholls et al., 2013). There are multiple dimensions that come into play in terms of research, the level of management (local, regional, national), and space and time (Nicholls et al., 2013).

Stakeholders in the management plan include businesses, industries, federal agencies, academics, fisheries, nonprofits, and the public (Peyronnin et al., 2013). It is important to consider businesses and residences that have been built in areas that would become future coastline (Nicholls et al 2013; Peyronnin et al., 2013). Stakeholder engagement is often difficult to put into practice (Nicholson-Cole & O'Riordan, 2009 as cited in Nicholls et al. 2013). The public needs to be engaged and educated on erosion (Nicholls et al., 2013; Peyronnin et al., 2013). Communities subject to erosion will need to be supported, possibly with government buyout of property and relocation of residents (Nicholls et al., 2013). All stakeholders should be considered and have the opportunity for involvement in the making of the management plan (Nicholls et al., 2013; Peyronnin et al., 2013).

Due to the many variables at play, management plans are ever evolving and need to include a regular monitoring program to adjust to the state of the changing environment (Nicholls et al. 2013). The Louisiana 2012 Coastal Master Plan is dynamic and flexible (Figure 5) and updated every 5 years to allow for changing environmental and social systems and for appropriate adjustments to be made when necessary (Peytonnin et al., 2013). It is essential to for the management team to have detailed information about the coastline in current time, as well as to know when changes occur, whether it be due to natural or human causes (Peytonnin et al., 2013). The timing associated with different actions to implement will depend on the rate of climate change and other unpredictable factors (Nicholls et al., 2013).

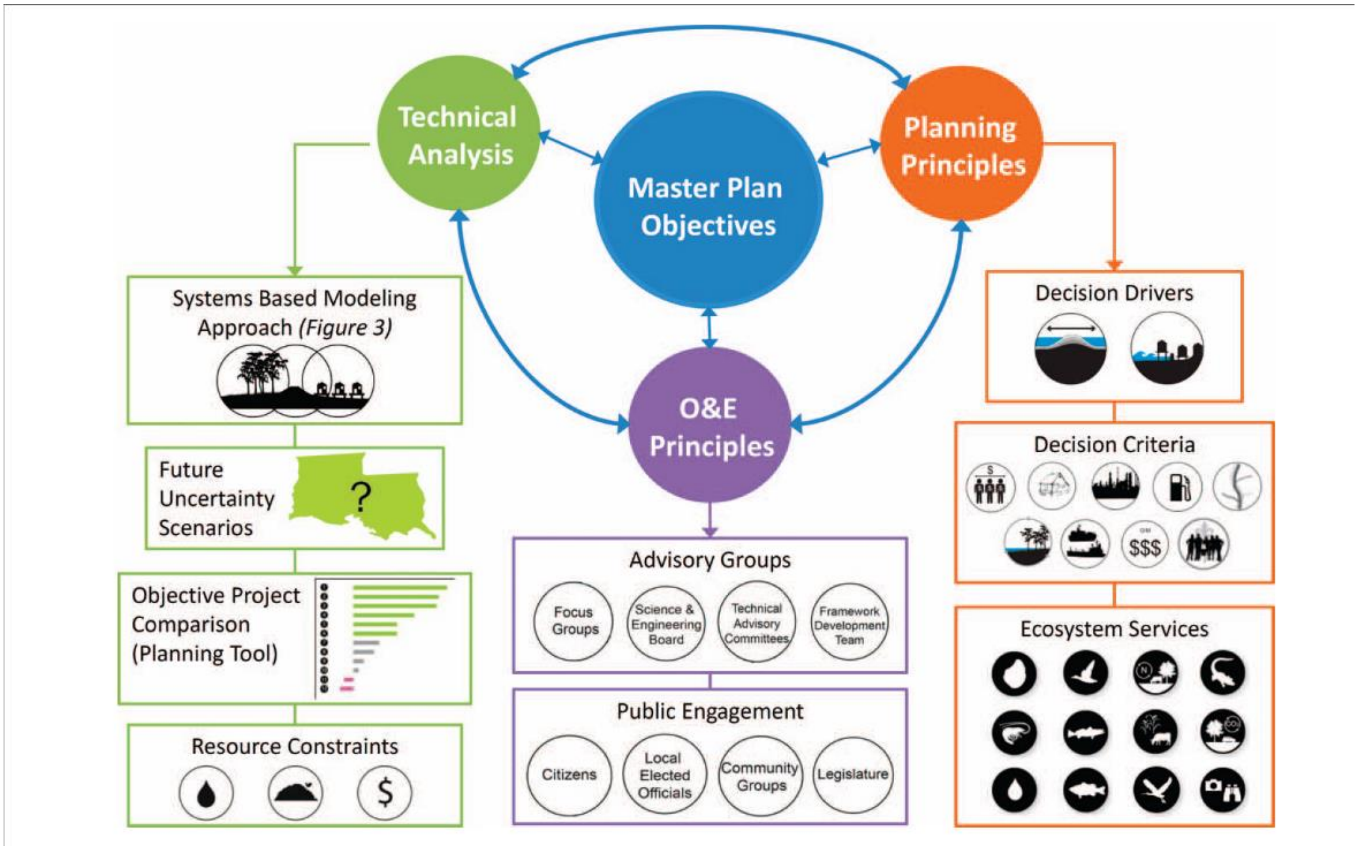

Figure 5: The interaction of input and feedback considered throughout the decision making process for Louisiana's Management Plan (Peytonnin et al., 2013).

5. Methodology

5.1 General Overview of Methods Used

A review of the literature indicates that an inventory of mangrove forest ecosystem for Oleta has not been performed previously. Use of aerial photographs to analyze ecosystem change is a frequently used technique (Kirui et al., 2013; Li, Meng, Ge, & Zhang, 2015; Sulong, Mohd-Lokman, Mohd-Tarmizi, & Ismail, 2002; Swetnam, Allen, & Betancourt, 1999; and many others). In this study, determination of changes in ecosystems was accomplished using 1) analysis of aerial photographs, 2) ground truthing, and 3) interviews with Oleta personnel. Some of the changes were documented losses related to development, others were gains related to mitigation. Present-day conditions were accessed to determine if rising seas poses a threat to the mangrove forest.

Historic imagery data was outlined to calculate mangrove coverage for available aerial imagery from 1961 to present. In person field surveys of the study site allowed for ground-truthing areas of mangrove cover, identifying Australian pine invasions and locating other mangrove stressors. An interview of an Oleta Naturalist provided further insight on the condition of the mangrove habitat and sea level rise concerns. The results from these analyses were used here to construct an integrate strategy for conserving mangrove habitats at the Oleta, with implications for managing forests throughout the region.

5.2 Mapping of Mangrove Extent Through Time

The change in mangrove area at Oleta was analyzed through a land cover analysis of aerial photographs from 1961 through present day using ArcGIS. The historic aerial photographs were acquired from the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) Aerial Photos Single Frame collection (www.glovis.usgs.gov); orthoimagery was acquired from USGS EROS Digital Orthophoto Quadrangle collection (https://earthexplorer.usgs.gov/). Maps of the Oleta field area were created in ESRI's ArcMap. Archival photographs from the Earth Explorer's Single Frame were imported into the maps and rectified into a WGS 1984 coordinate system. Feature class polygons were created for the mangrove habitat for each time frame and compared to determine change in area over time. Two polygon types were created: full mangrove cover (>50%) and partial mangrove cover (<50%) (Figure 6). An area field was added to the polygon shapefile's attributes table (type: long

integer; precision: 9). Calculate geometry was performed on this area field to produce area values in meters squared. This was converted into kilometers squared for graphic purposes.

The multiple polygon outline area values for each time frame were entered into an Excel spreadsheet to sum the total cover for the respective year, then converted into kilometers squared. The data calculated included: full cover, partial cover, total cover and percent loss compared to the oldest image from 1961. Values for area at each time were tabulated and graphed. This produced a table and two line-graph figures. Some areas were hard to distinguish between mangrove trees and other foliage. Areas with unclear foliage were marked in a point shapefile as “areas of interest” to visit in person for verification (Figure 7).

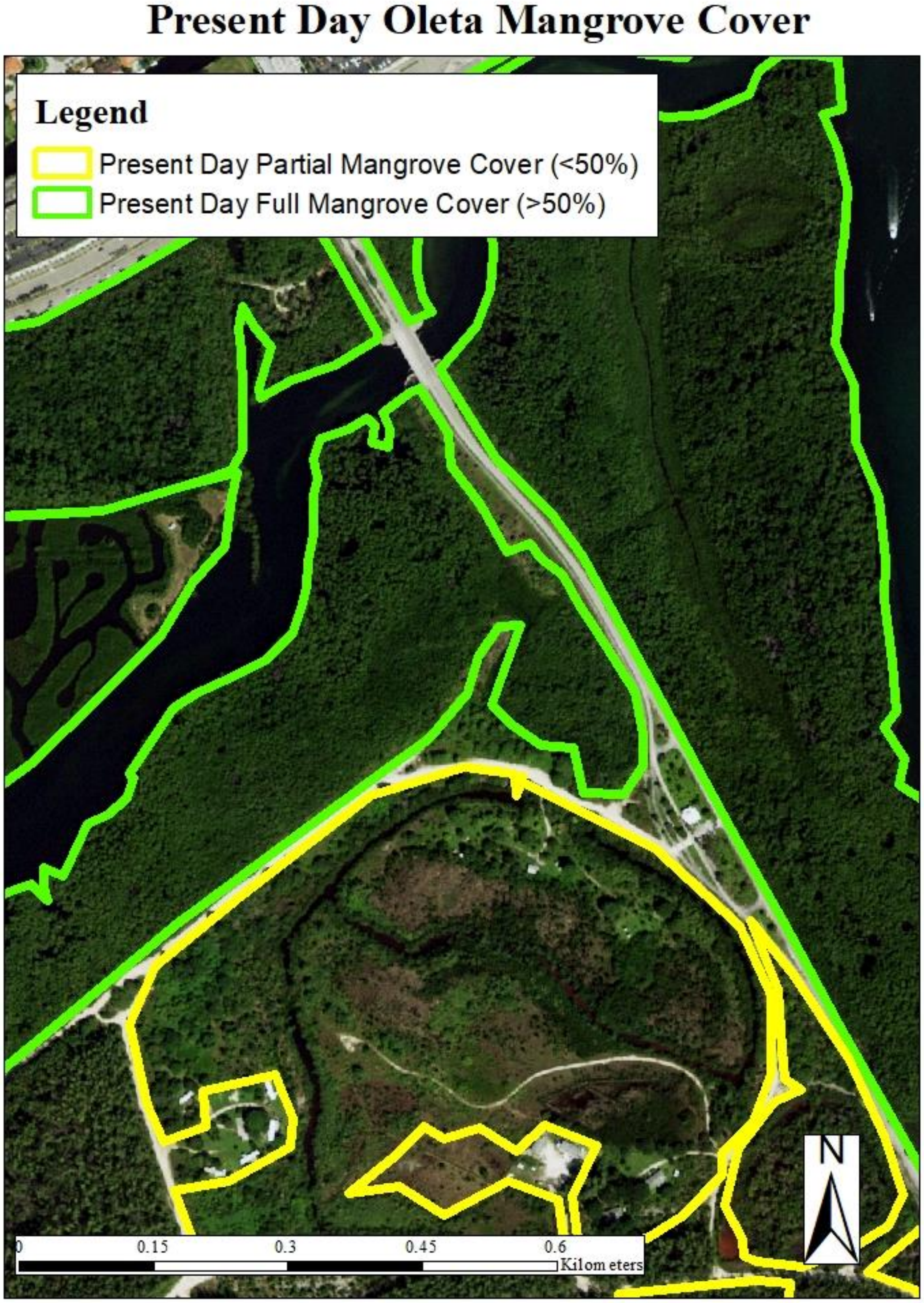

Figure 6: A graphic representation of the method of area calculation within ArcGIS.

Figure 7: Tree species which were hard to distinguish in the aerial imagery were marked as “areas of interest” to visit in person.

5.3 Determination of Mangrove Change Cause

To determine total change in mangrove forest area since 1961, ArcMap was used to create polygons using both 1961 and 2017 aerial imagery. These were toggled on and off to create polygons outlining the remaining mangrove area seen today, the areas which have been lost due to development, Australian pine, and change in shoreline.

Within ArcMap, the 2017 image layer along with the 1961 mangrove area layer were used to create polygons outlining areas with development, dredging and Australian pine which were previously mangrove area. The 1961 mangrove area polygon overlaid on top of the 2017 aerial imagery allowed for the polygon illustrating change in shoreline to be created.

To visualize the extent of change in shoreline since 1961, another map was created. This was created by using ArcMap with the 1961 historic shoreline over top of the present-day background.

5.4 Ground Truthing

To verify identification of mangrove and other tree species, as well as to assess the health of the stands, assessible areas of the field area were groundtruthed. Not all areas of Oleta are accessible due to thick undergrowth and waterlogged soils, but the fringe of the forests were visited and used for verification of species, maturity, and forest health. Georeferenced photographs of living and dead mangroves were collected, as well as representative Australian pines and other invasive species, for comparison with imagery and for tree height calculations. Georeferenced photographs were imported to create point shapefiles to incorporate into ArcMap. Geotagged photos appear on the map as points in the georeferenced location where the photograph taken. These were viewed in ArcMap using the “html popup” tool (Figure 8). A new feature class was created and brought into the map for each kind of observation: white mangrove, black mangrove, red mangrove, seedlings, Australian pine, drowned tree, fallen tree, and tree height measurements (Figure 9).

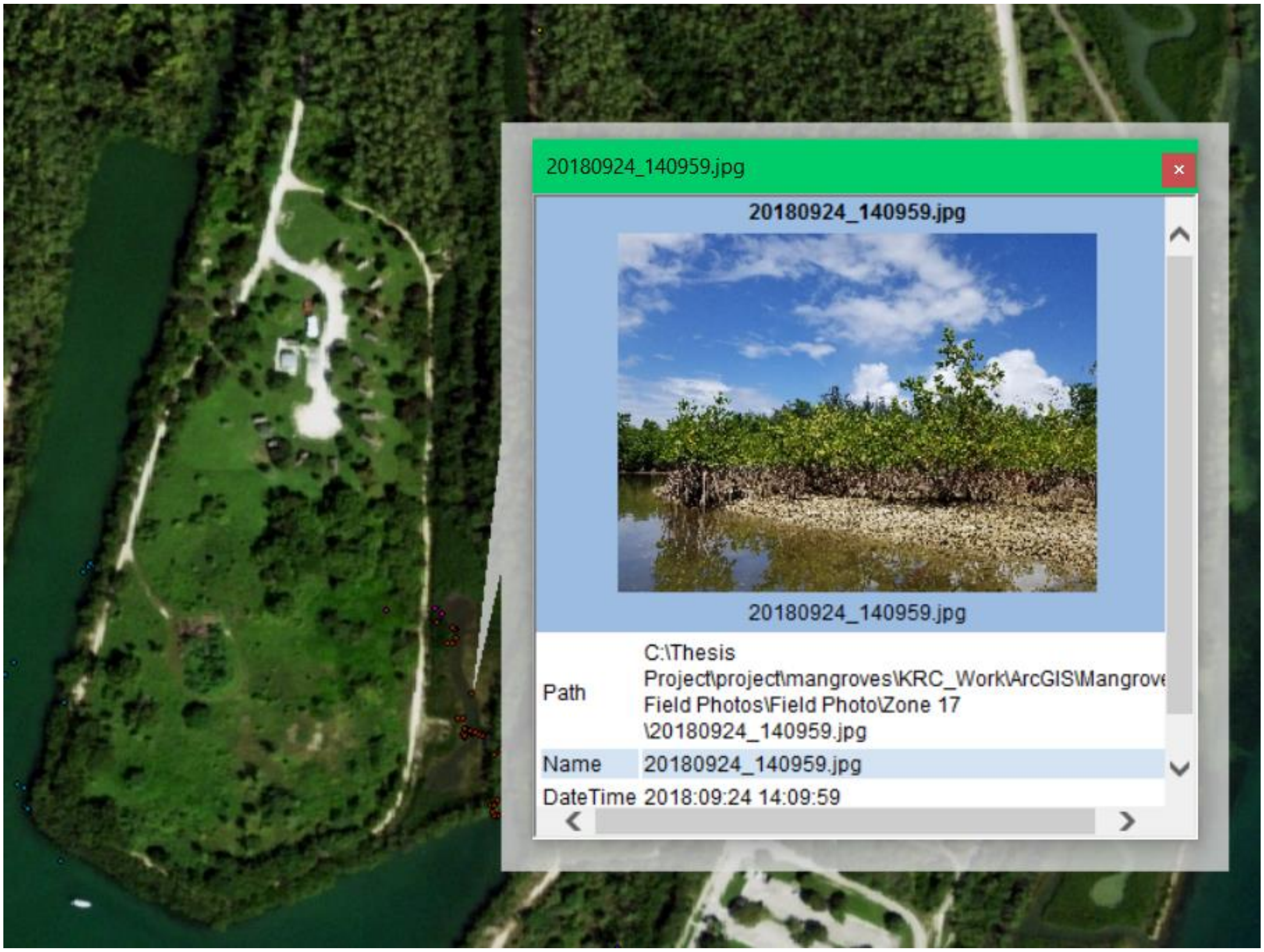

Figure 8: The photos map with a geotagged photograph displayed.

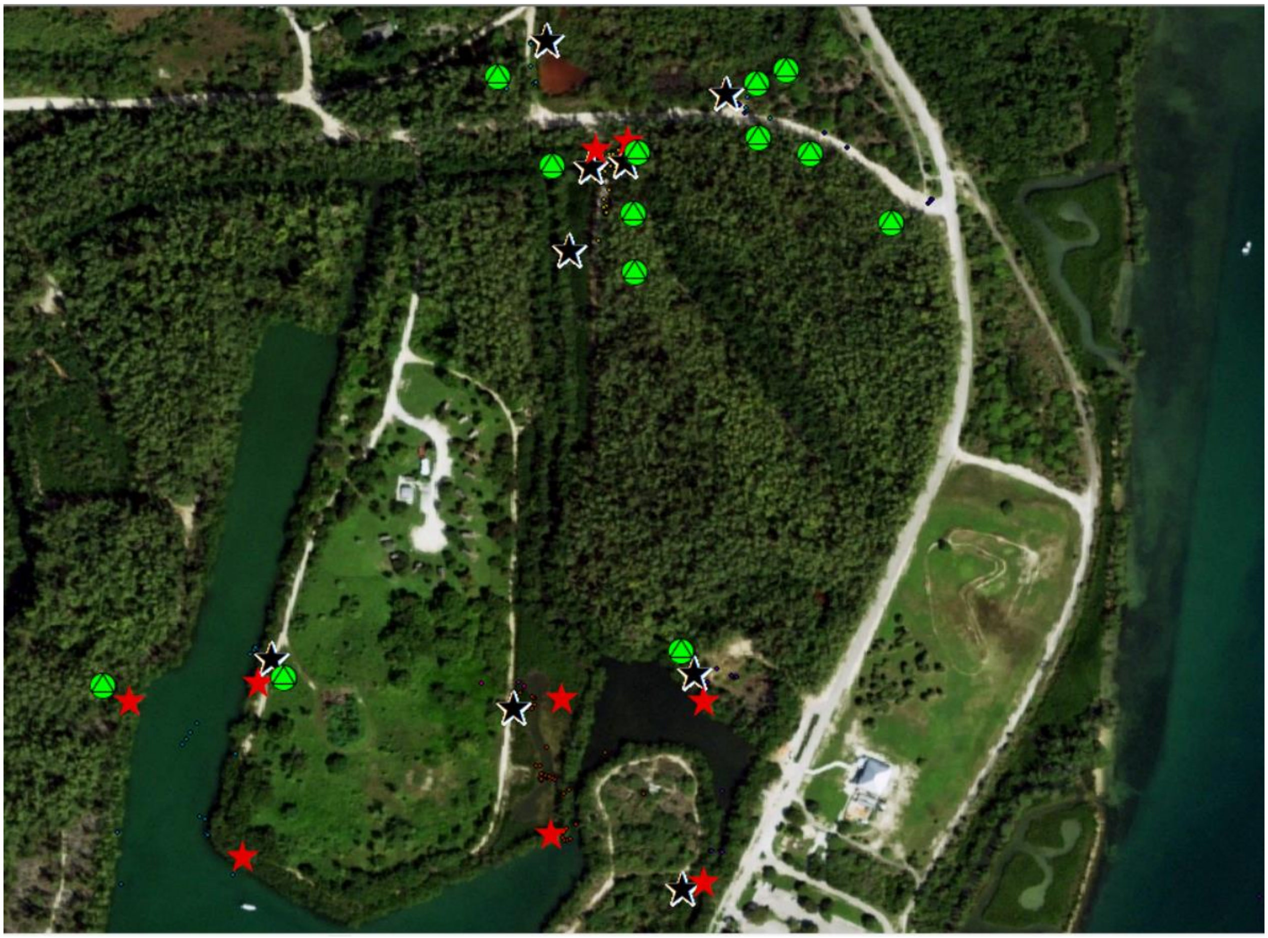

Figure 9: The geotagged photos map with the point icons indicating different tree species.

Tree heights are useful indicators of the maturity of tree stands. Both mangrove and Australian pine height measurements were taken. Tree height estimates were made using the app "Dioptra" (Figure 10) to acquire the angle to the top of a tree, and distance from the camera to the tree calculated using measuring tape. The distance from the tree, angle to the top of the tree, and the height of the photographer was used to calculate tree height using the sine method (Bragg, Frelich, Leverett, Blozan, & Luthringer, 2011):

$$\tan(angle) * distance(m) + height\ of\ photographer(m) = tree\ height$$

Tree heights were represented within ArcMap by creating a height icon within a point shapefile which was placed next to the photograph point where the tree heights were measured. This was represented in a figure by adding a text field in Layout view with the tree species and calculated height.

Figure 10: Photograph using Dioptera App to get the tan angle.

5.5 Interview with the Oleta Naturalist

The Oleta Park Naturalist, Jacob M. Bennett was interviewed on June 10th, 2017 (personal communication). Information inquired included 1) his knowledge on flooding in Oleta, 2) what mangrove stressors were known, and 3) mangrove restoration projects. This interview was recorded to accurately summarize in the results.

6. Results

6.1 General

Mangrove cover was calculated using ArcGIS using archival aerial imagery for the years 1961, 1969, 1972, 1979, 1986 and 2017. Total mangrove cover has fluctuated over this time, but ultimately resulted in a 42%, 3 km^2 total loss. The width at a location along the Oleta River was calculated, using the measurement tool within ArcMap, to be an increase in 32 m between 1961 and 2017. The area is under stress, including extensive development, Australian pine forest encroachment, and mangrove die off.

6.2 Mapping of Mangrove Extent Through Time

For each image year, full cover and partial cover were calculated (Figures 11-16). Full cover is defined as being greater than 50% cover and partial cover is defined as being less than 50% cover. Total mangrove area is the sum of the partial and full mangrove cover in kilometers squared. The change in cover compared to previous year was calculated by subtracting the previous year's total with the current year's total. The percent change compared to 1961 mangrove cover was calculated as the percent change in area between the current year and the area in 1961. The area calculations in ArcGIS provides detail to the 5^{th} decimal place since an area could only be accurately determined to the nearest tenth of a square kilometer.

Table 1: Data collected from polygon analysis.

Year	Full Mangrove Cover (Km^2)	Partial Mangrove Cover (Km^2)	Total Mangrove Area (Km^2)	Change in cover compared to previous year (Km^2)	% Change Compared to 1961 Mangrove Cover
2017	3.6	0.6	4.2	-1.9	-42%
1986	4.0	2.1	6.1	1.5	-15%
1979	4.0	0.6	4.6	-0.7	-35%
1972	4.5	0.8	5.3	1.7	-26%
1969	3.4	0.3	3.7	-3.5	-49%
1961	6.9	0.3	7.2	null	0%

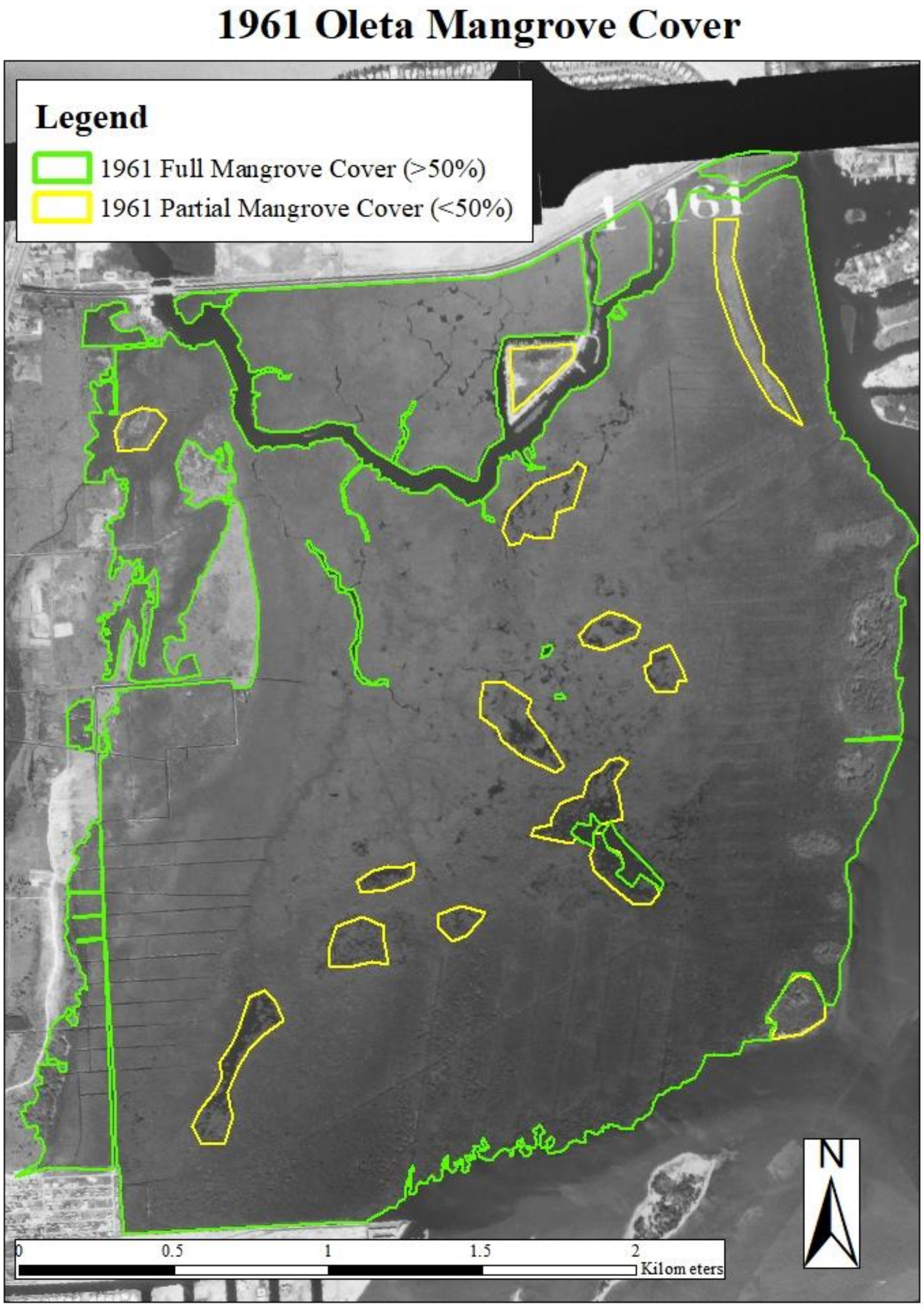

Figure 11: Mangrove cover from 1961. Full mangrove cover is 6.9 km^2, partial mangrove cover is 0.3 km^2, and total mangrove area is 7.2 km^2.

1969 Oleta Mangrove Cover

Figure 12: Mangrove cover from 1969. Full mangrove cover is 3.4 km^2, partial mangrove cover is 0.3 km^2, and total mangrove area is 3.7 km^2.

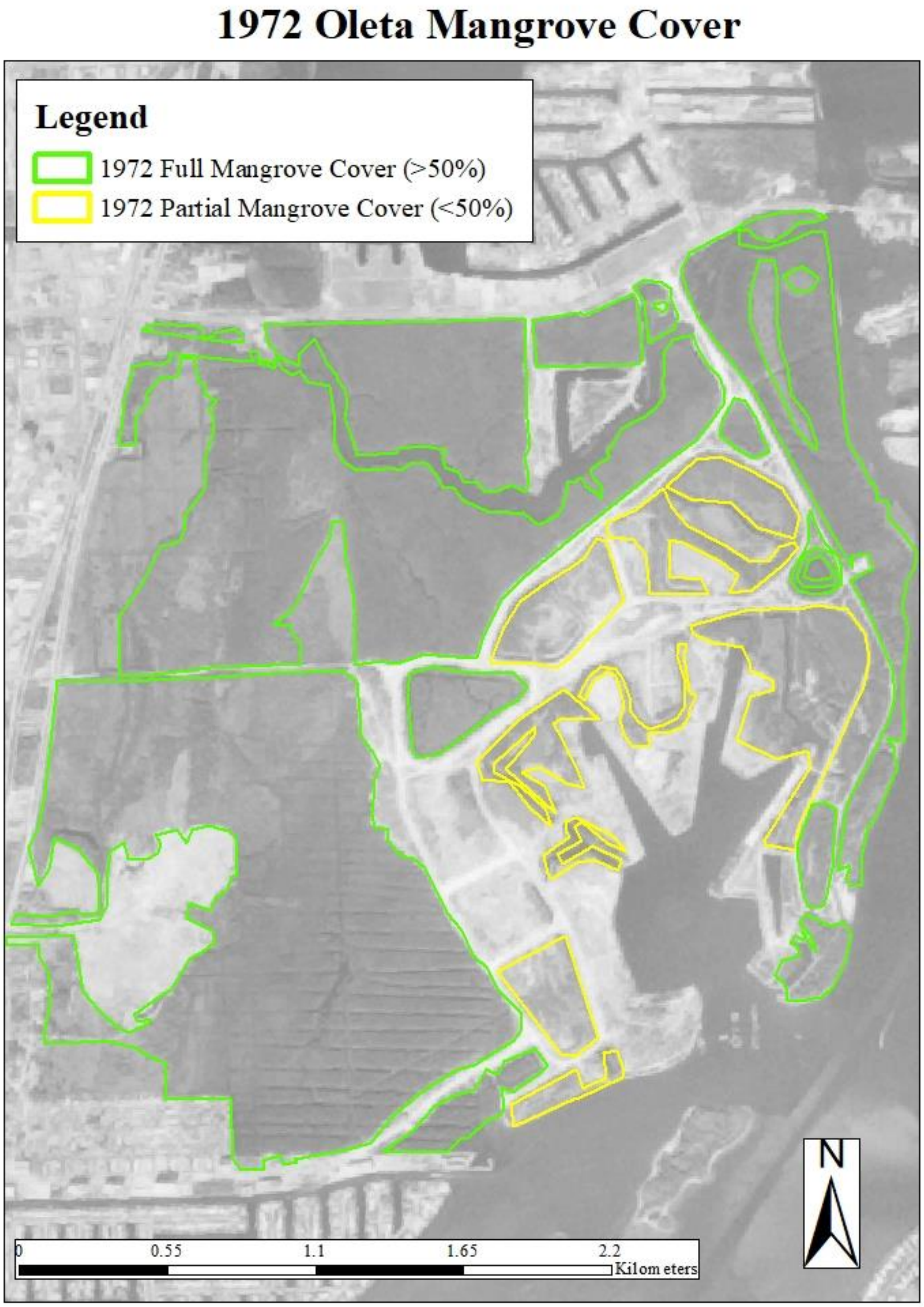

Figure 13: Mangrove cover from 1972. Full mangrove cover is 4.5 km^2, partial mangrove cover is 0.8 km^2, and total mangrove area is 5.3 km^2.

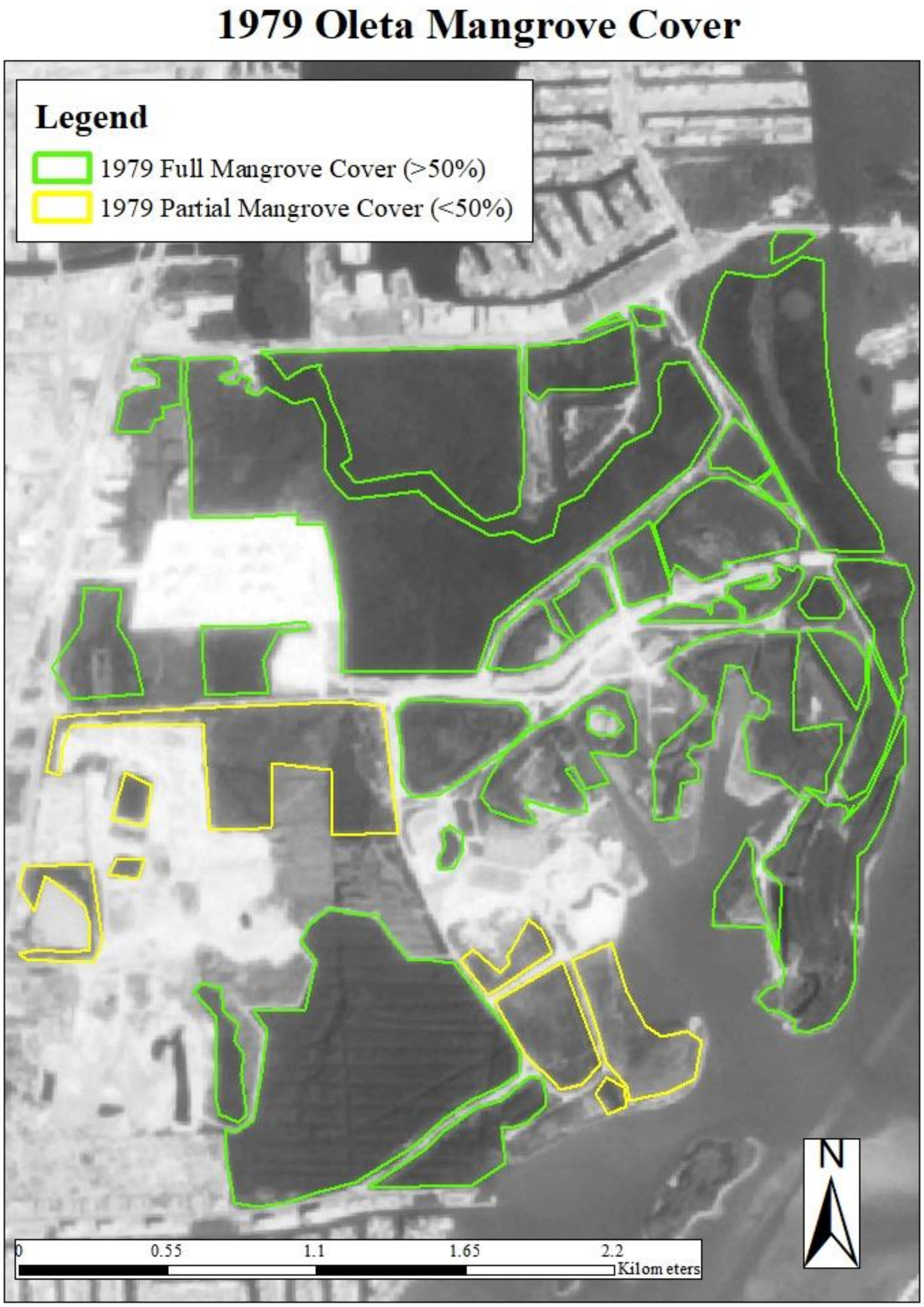

Figure 14: Mangrove cover from 1979. Full mangrove cover is 4.0 km^2, partial mangrove cover is 0.6 km^2, and total mangrove area is 4.6 km^2.

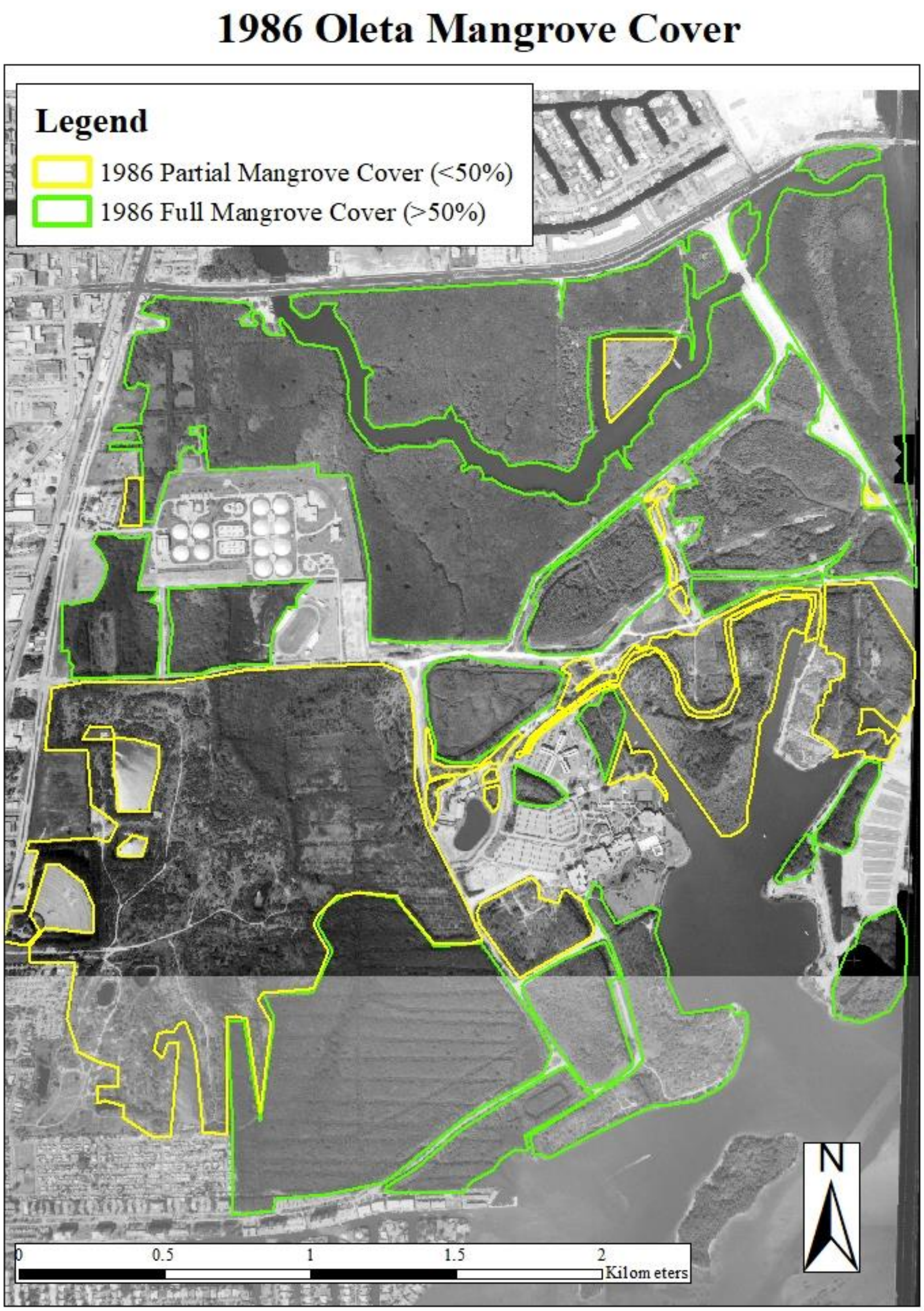

Figure 15: Mangrove cover from 1986. Full mangrove cover is 4.0 km^2, partial mangrove cover is 2.1 km^2, and total mangrove area is 6.1 km^2.

Present Day Oleta Mangrove Cover

Figure 16: Mangrove cover from 2017. Full mangrove cover is 3.6 km^2, partial mangrove cover is 0.6 km^2, and total mangrove area is 4.2 km^2.

The total mangrove area at Oleta has fluctuated over the past 50 years (Figure 17). In 1961, at the time of the earliest available aerial imagery, total mangrove area was 7.2 km^2. The total area decreased in 1969, totaling 3.7 km^2. The mangroves began to recover again, repopulating previously cleared areas, in 1972, totaling 5.3 km^2. In 1979, the mangrove population decreased to a total area of 4.6 km^2. The total mangrove area increased again in 1986 to 6.1 km^2. The total mangrove area decreased again with a total of 4.2 km^2 in 2017.

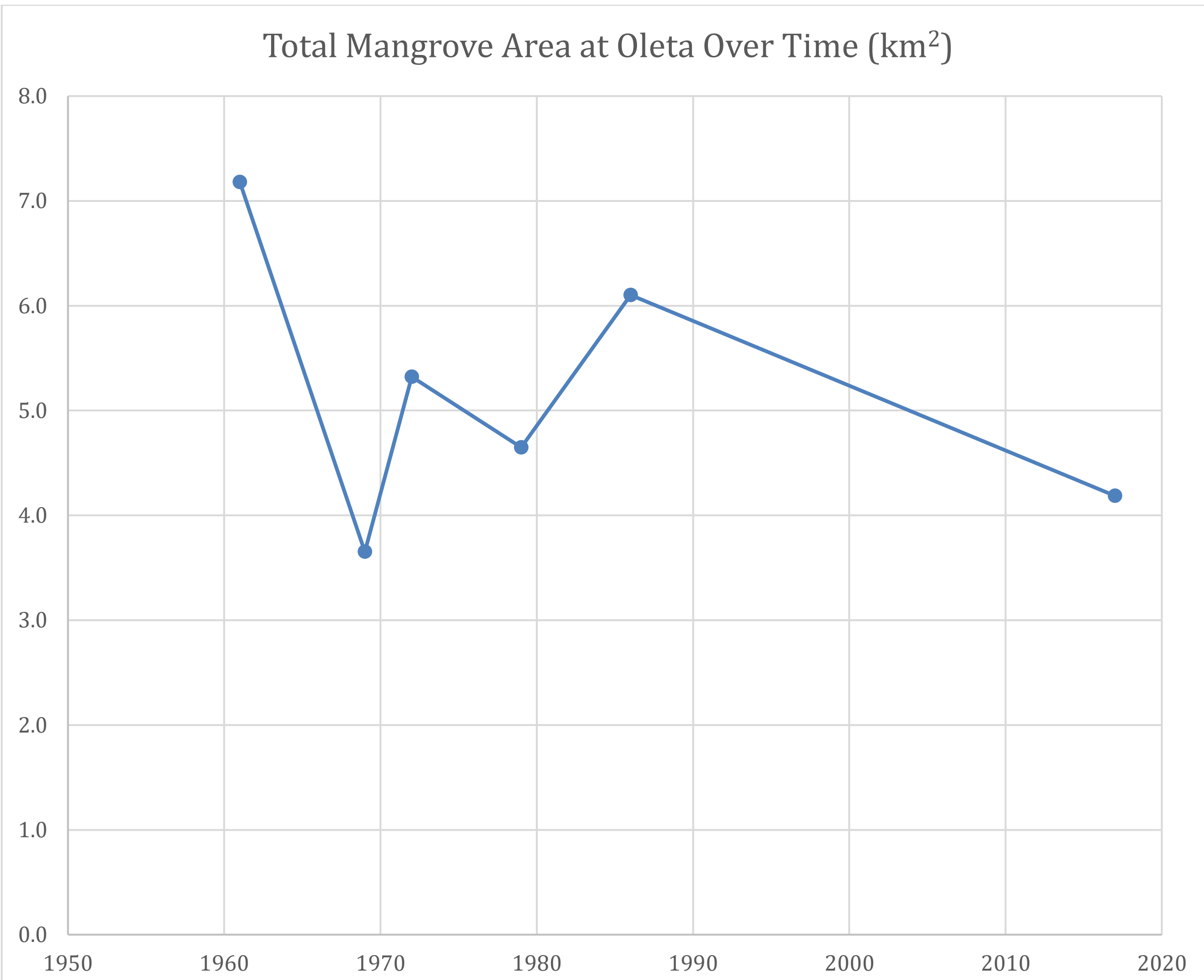

Figure 17: The change in total mangrove area from multiple year intervals between 1961 and 2017, shown in km^2.

The trends of full and partial change in mangrove cover between the analyzed aerial imagery time intervals is illustrated in Figure 18, with exact area values in Table 1. Full mangrove cover is represented by mangrove areas with 50% or more cover; partial mangrove cover is represented by less than 50% mangrove cover. Between 1961 and 1969, full mangrove cover decreased from 6.9 km^2 to 3.4 km^2, while partial cover remained the same, 0.3 km^2. From 1969 to 1972 both full and partial mangrove cover increased, from 3.4 km^2 to 4.5 km^2; and 0.3 km^2 to 0.8 km^2, respectively. Between 1972 and 1979 there was a decrease in full mangrove cover, 4.5 km^2 to 4.0 km^2, and partial mangrove cover, 0.8 km^2 to 0.6 km^2. From 1979 to 1986, full mangrove cover remained 4.0 km^2, with an increase in partial mangrove cover, 0.6 km^2 to 2.1 km^2. Both total mangrove cover and partial mangrove cover decreased between 1986 and 2017: 4.0 km^2 to 3.6 km^2, and 2.1 km^2 to 0.6 km^2, respectively.

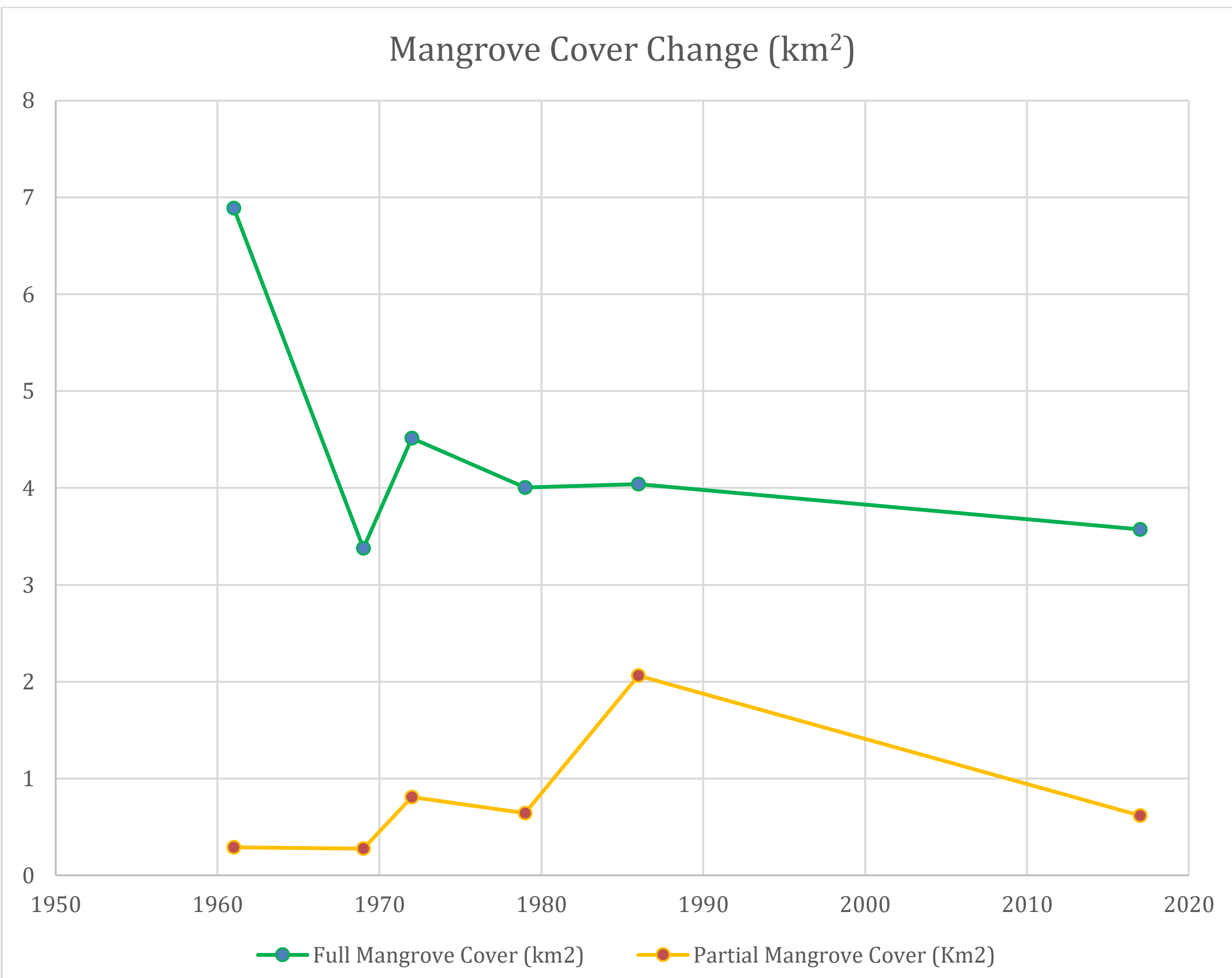

Figure 18: The change in full vs. partial mangrove cover for the indicated years.

6.3 Determination of the Change in Mangrove Area Compared To 1961

The coastline of mangroves at Oleta between 1961 and present-day were compared in Figure 19. The present-day aerial imagery has the outline from the 1961 polygon displayed on top to visualize the change in shoreline. There is a clear widening of the Oleta River visible. A polygon image was created to illustrate the mangrove area remaining and the area lost, and due to what cause (Figure 20). Table 2 shows the areas analyzed in km^2. Figure 21 displays the current area percentages in a pie chart. The remaining mangrove area from the 1961 mangrove forest is 4.4 km^2, or 56% of the original cover. Dredging during the Interama project accounted for a loss of 0.4 km^2, or 6%. Development has caused the greatest loss of 1.9 km^2, accounting for 25% of the original forest cover. The Australian pine invasion is significant, nearly 1 kilometer squared (0.9 km^2), accounting for the loss of 11% of the original mangrove habitat. The shoreline has clearly receded, resulting in a loss of 0.2 km^2 or 2% of the original habitat.

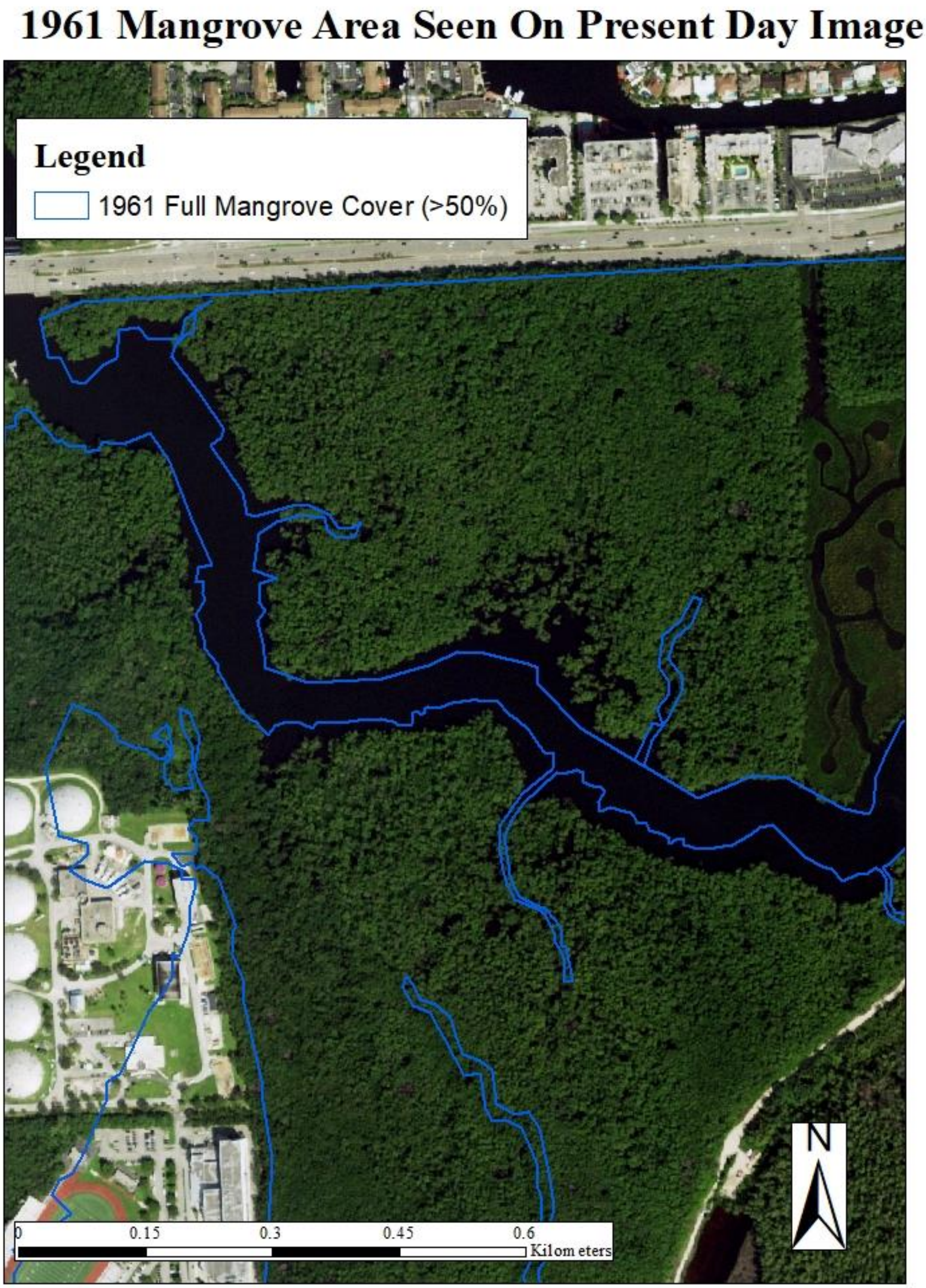

Figure 19: The widening of the Oleta River illustrated by the 1961 mangrove area outline displayed upon aerial imagery from 2017.

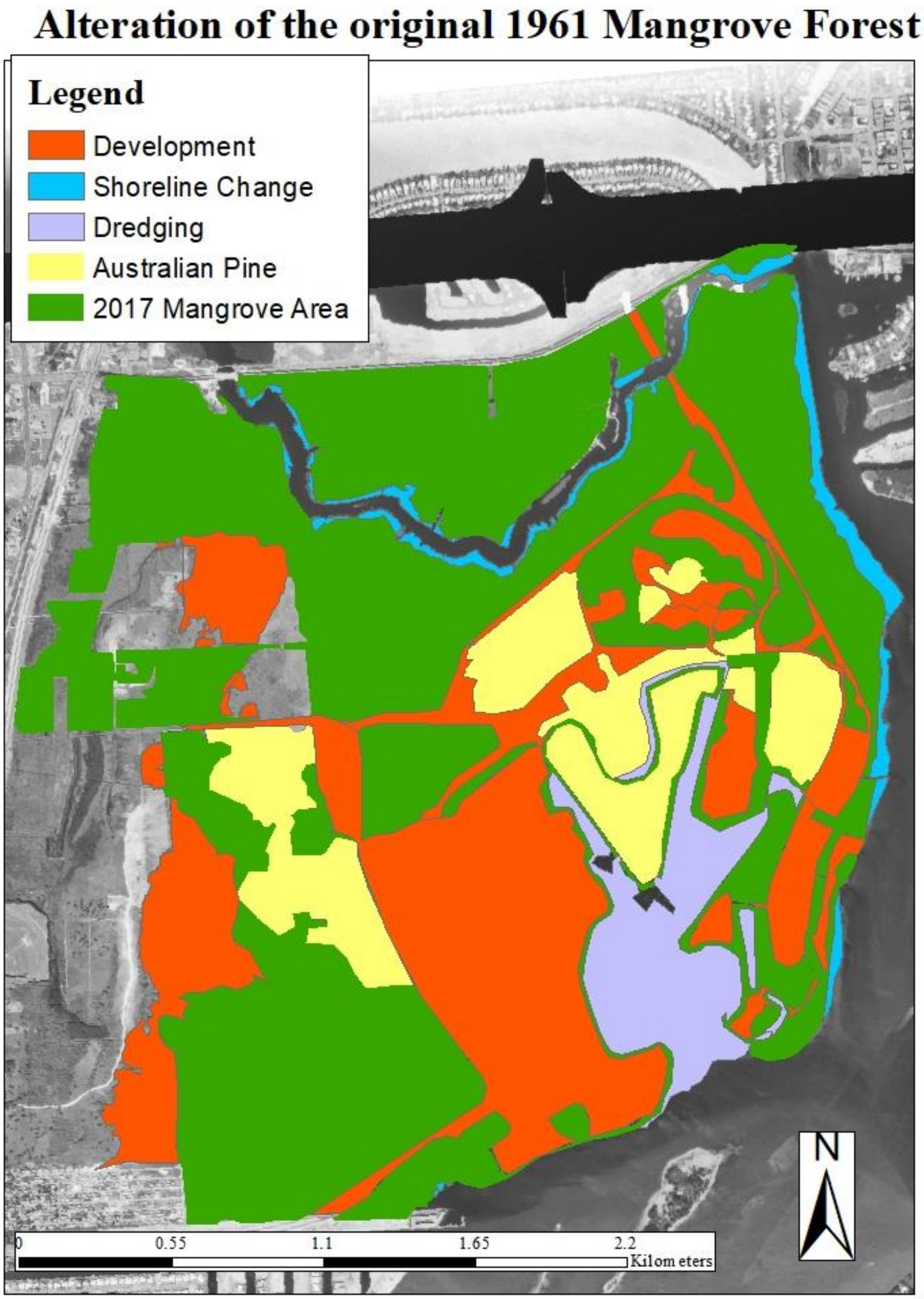

Figure 20: The present-day alteration of the 1961 mangrove forest, represented by polygons depicting the cause of the mangrove loss.

Table 2: Area of remaining mangrove and cause of loss compared to 1961.

	Development	Dredging	Australian pine	Shoreline Loss	Remaining Mangrove
Area (km^2)	1.9	0.4	0.8	0.2	4.4

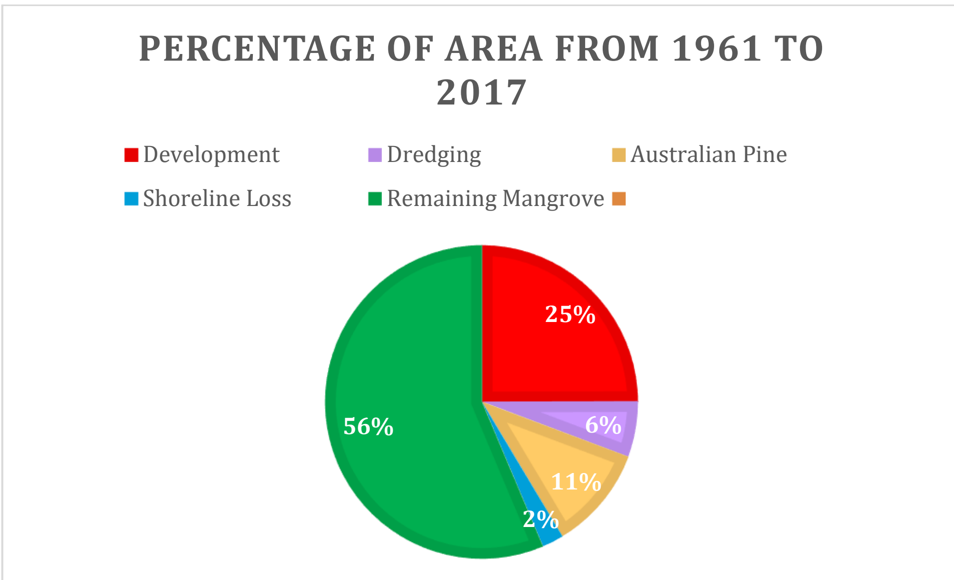

Figure 21: The coverage of remaining mangrove area since 1961, along with the areas lost.

6.4 Field Study

6.4.1 Species analysis.

Figure 22a and 22b show the results of the analysis of the photographs taken at the field. There are many areas with prevalent invasive Australian pine trees along the fringes of mangrove forest. In some areas, they have formed their own forest, devoid of other species (Figure 23). In addition, the invasive species beach naupaka was also present or identified in the western extent of Oleta. All three species of mangrove were present: red mangrove, black mangrove and white mangrove. There was erosion seen at the southernmost extent of the park, subject to high wave energy. A methane seep was also found.

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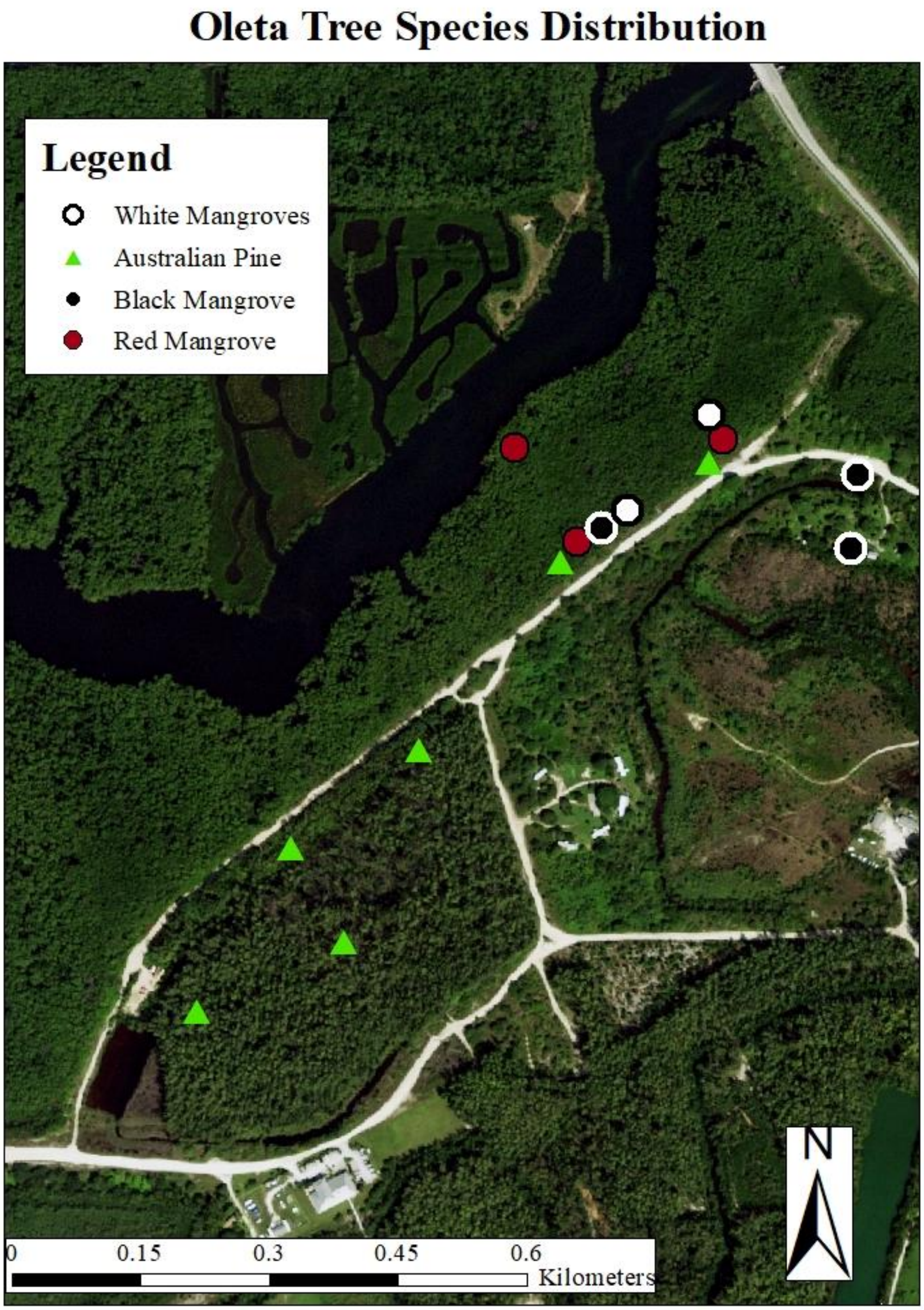

Figure 22a: Photograph embedded map with points depicting the ground truthing.

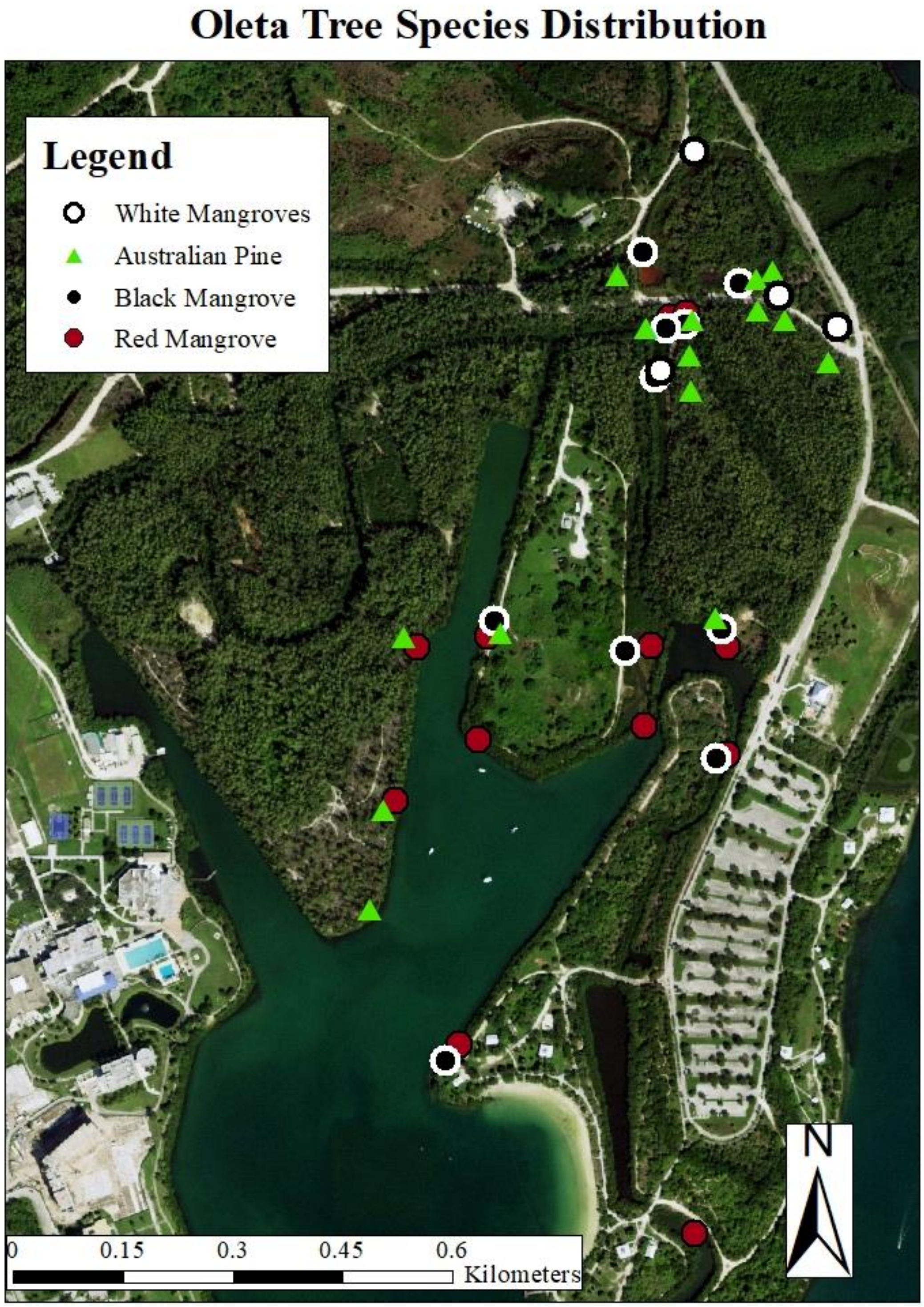

Figure 22b: Photograph embedded map with points depicting the ground truthing.

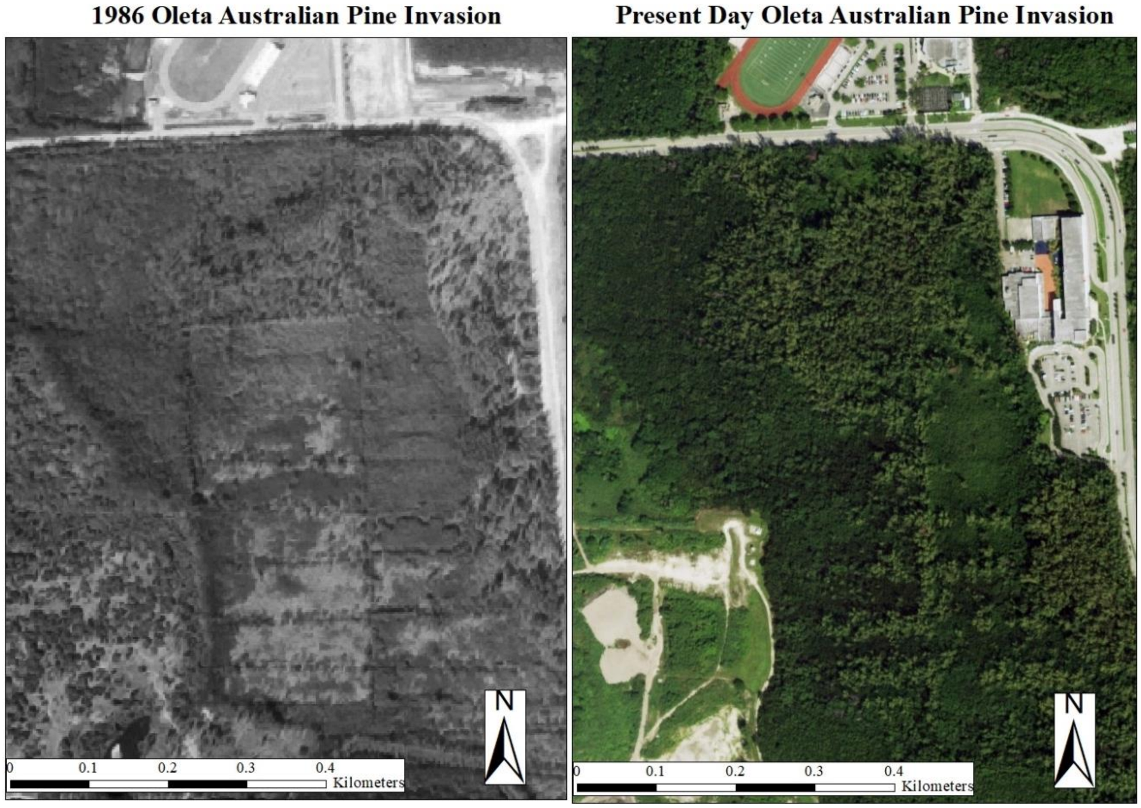

Figure 23: Shows the beginning of Australian Pine encroachment into a Mangrove Forest (1986 on Left; Present Day on Right).

6.4.2 Tree height measurements.

Six tree height measurements were taken (Table 3). The mangroves surveyed at Oleta are around 6-8 meters tall, indicating a mature stand comparable to the mangrove forest in Everglades National Park (Simard et al., 2006). The Australian pine trees surveyed had much taller trees, reaching 27.7 meters tall, this indicates the Australian pine stand is mature (Xie, Roberts, & Johnson, 2008) and prevalent at Oleta.

Table 3: Various tree height measurements taken at Oleta.

Tree Species	Calculated Tree Height (m)
Black Mangrove	6.9
Black Mangrove	8.5
Red Mangrove	8.7
Australian Pine	27.7
Australian Pine	10.0
Australian Pine	23.6

Figure 24: Tree height measurement results.

6.4.3 Interview with the Oleta Naturalist.

The following information was acquired during an interview with Jacob Bennett, the Oleta Park Naturalist, on local concerns regarding the mangroves. Bennett noted that it is possible the park is already experiencing negative effects from rising sea levels; this area is extremely flood prone. All the canals, certain roads within the park, the ranger station parking lot and the entire beach will flood during the highest tides of the year, called King Tides.

There is an area of mangroves which have largely died off, referred to as the "dead zone" by Bennett. This patch of mangroves originally had a drainage canal which would allow the tidal influx to come in to supply the mangroves with saltwater, it has since been impacted. With freshwater influx from rain and decreased nutrient input from the clogged canal, the mangroves perished. Bennett estimated this dead zone at less than 1 hectare. Some smaller mangroves on the outskirts of that pond and a few sporadic larger ones are still living mangroves, but according the naturalist, over 99% of the mangroves in that area have died. Oleta management, working with DERM's Josh Mahoney, a different environmental agency through the county, was applying for grants in efforts to set up a couple hundred thousand dollar project to fund a new canal and prefabricated bridge to allow the tidal influx back to that area.

It is difficult locating areas for planting new mangroves, seedlings are washed away with high tides. Most of the mangrove saplings planted by local elementary and middle schools have been washed away during times of flooding according to Bennett, although some survive. Bennett recommends this be taken into consideration when proposing management solutions.

There are multiple sources of negative anthropogenic effects. A sewage treatment facility near Oleta has leaked twice, resulting in a temporary Oleta shut down. Illegal cutting of mangroves has been observed with fishermen seeking better access to the river. Enforcement is difficult because the authorities are often unable to find the culprits.

6.4.4 Stressed mangrove evaluation

Fallen or dead trees found in the field survey were photographed and marked in the geotagged map (Figure 25). An entire section of dead mangroves, referred to at Oleta as the "dead zone", is due to anthropogenic stress. There was a large drainpipe which would allow sea water influx to this zone that became clogged. With the influx of sea water from tides cut off, over time freshwater input from rainfall decreased the salinity of this area as well as nutrient

input, potentially causing the death of mangroves in that location.

Figure 25: Fallen or dead trees seen in the field study.

7. Discussion

7.1 Mangrove Extent Through Time

The mangrove population at Oleta has suffered a significant loss of 3 km^2, amounting to 42% total area loss since 1961, largely due to human development. Oleta mangrove accretion rates are low with a poor influx of sediments due to the low-lying coastal nature with anthropogenically altered historic river outputs. The historical imagery analysis shows a significant loss in mangrove habitat over the last 60 years. The image analysis also indicates a clear receding of the shoreline over time, the Oleta river was estimated to have widened by 32 meters. According to the relative sea level tide data from the NOAA station in Key West, Florida, sea level has risen by 0.243 m between 1961 and 2017. Loss could be due to the increasing sea level and associated increase in erosion, supporting the hypothesis that rising sea level is a vulnerability to the mangrove habitat at Oleta.

The mangrove forest at Oleta had an area of 7.2 km^2 in 1961 before the Interama project, which reduced the mangrove area 49% by 1969. This project caused the entire total loss of 3.5 km^2, resulting in a mangrove forest total area of just 3.7 km^2 . While the project was never completed, it left wide canals, an open water lagoon and elevated uplands.

Over the next three years, from 1969 to 1972, mangroves regrew by 1.7 km^2, resulting in a total mangrove area of 5.3 km^2. This is likely due to the failure of the Interama project, as the majority of the regrowth, at least 75%, is from areas within the Interama area.

Throughout the majority of the 1970s, from 1972 to 1979, mangrove area again decreased by 0.7 km^2, with a total mangrove area of 4.6 km^2. Measurements of the aerial imagery show a loss in mangrove area of 0.3 km^2 due to the development of a wastewater treatment facility towards the northwest extent of Oleta. The loss due to the Munisport Landfill development on the central west extent of Oleta totaled 0.7 km^2. The loss due to both developments, 1.0 km^2 is greater than the total loss because the loss was offset by 0.3 km^2 gain in the central east section of Oleta.

There was an increase in mangrove area from 1979 to 1986 of 1.5 km^2, resulting in a total mangrove area of 6.1 km^2. There was no change in full mangrove cover, the increase is from partial mangrove area increase alone. This is seen in the imagery as land previously cleared was recolonized by mangroves in the southwest extent of Oleta, being less than 50% so recorded as partial mangrove cover. Mangrove stands on the west side of the park also increased in area.

Mangrove area has been again decreasing since 1986: with a loss of 1.9 km^2 in area from 1986 to 2017 and a total mangrove area of 4.2 km^2. This is due to increased development with Sole Mia, located to the west of the Munisport Landfill, accounting for 0.9 km^2 of the loss, development within the Florida International University East Campus, accounting for a loss of 0.5 km^2 and extensive Australian pine growth seen in the imagery, which encroached on 0.5 km^2 of previously colonized mangroves. A restoration project in 2007 helped to mitigate the Australian pine damage by removing the invasive species and planting mangroves in an area estimated 0.07 km^2 (Miami-Dade County Division of Environmental Resources Management, 2007).

The imagery analysis clearly illustrates widening of the Oleta River, along with an estimated 32 km increase in river width since 1961, supports the hypothesis that sea level rise is a vulnerability of Oleta.

This study is limited by the availability of only specific images in time. Some images are very close in years while there are large gaps between others. Additionally, it is impossible to ground truth the past, only make inferences based on the present condition and species composition.

7.2 Field Study

The field study analysis was to assess the current health and maturity of the mangrove population at Oleta to gain further insight into its management needs, as well as to ground-truth the work done in the historical imagery analysis. Areas which appeared to be Australian pine in the aerial photographs were confirmed with this field study. Field studies are limited by only being able to analyze accessible areas.

All three Florida mangrove species are present within Oleta. The mangrove forests are well developed with mature mangrove trees averaging 6-9 meters in height. The mangrove habitat at Oleta is under stress from invasive species, as many Australian pines were found. The Australian pine sightings included new younger Australian Pine growth, along with areas of well-developed Australian pine forests with very large trees reaching 28 meters. Younger Australian pine trees were sighted near the fringes of mangroves, indicating the beginning of new encroachment on the mangrove habitat. It is not a surprise Australian pine trees are proliferating; the success of Australian pine in saline soils and windy areas has been

documented (Bezona et al., 2009). The well-developed areas of Australian pine trees had outcompeted all other foliage by creating their own forests in the upland areas of Oleta.

Most of the mangrove trees appear to be healthy. Fallen and dead trees noted in the field study were recorded with their location marked via a geotagged photograph. A problem with a clogged drainage pipe resulted in the death of an entire section of mangroves. Dead mangrove trees were sighted in other areas of the park as well. People coming to fish have been known to cut down mangrove trees illegally in this area. Boat wake has also caused erosion. The mangroves are subjected to pollution from a nearby sewage treatment facility leakages. Flooding is an issue at Oleta with many roadways, parking lots and the public beach becoming flooded during king tides. Mangrove restoration at Oleta is difficult as most of the saplings end up being washed away.

Development has decreased the 1961 mangrove forest by 25%, 31% if you include dredging of the canals. Australian pine growth has invaded 11% of the mangrove forest, totaling 0.9 km^2. The shoreline has clearly receded, accounting for a loss of 0.2 km^2, or 2% of the habitat since 1961. The sea level is rising at a rate faster than mangroves can keep pace, and without sufficient sediment input in this region, the mangroves will not be able to keep up with this impending change. The various stress factors found in the field study supports the vulnerability of the mangroves at Oleta to impending sea level rise because any stress decreases a habitats resilience to change. This supports the hypothesis: since this mangrove habitat appears to be vulnerable to climate change induced sea level rise, management plans regarding resilience to sea level rise are necessary.

8. Conclusions

8.1 Data Analysis Conclusion

If it is true that the mangrove habitat at Oleta is vulnerable to sea level rise, then a management plan regarding the resilience to impending sea level rise should be created. Despite the intervals of mangrove growth, the area lost since 1961 amounts to 42%, or 3 km^2 through environmental degradation by human infrastructure as well as widening of the rivers by, potentially, rising seas. The review of historic imagery and field surveys discovered that the mangrove habitat at Oleta is threatened by many stressors, including climate change induced sea level rise.

Mangroves are known to only be able to keep pace with a sea level rate of less than 1.2 mm/yr, given there is enough sediment input (Ellison and Stoddart, 1991). The local rate of sea level over the past 89 years was 2.92 mm/yr (NOAA station at Virginia Key). Since the current rate of sea level rise is 3.6 mm/yr and projected to increase (IPCC, 2019), and the sediment input is not sufficient (Schuerch et al., 2018), with no space for inland migration, the mangrove forest at Oleta is threatened by sea level rise. Its resilience is decreased due to various stressors including invasive species, pollution, habitat degradation, and erosion. The mangrove population at Oleta is threatened by sea level rise because the ability to build soil vertically is low and the space for inland migration is non-existent. The best, and arguably only, solution would be to provide for inland migration of Oleta's mangrove forest through the repurposing of developed areas. Development will need to be altered into natural areas to allow for managed retreat. This would be most beneficial in areas which are projected to become flooded in the near future. However, efforts should be made to first focus on converting Australian pine habitat into greenspace for inland migration of mangroves. Converting the adjacent buildings and roadways into greenspace will be a large project needed further into the future. Removing the invasive Australian pines for future mangrove habitat is more pressing and should be addressed first.

An analysis over time is valuable and would be useful to other studies as well. The current condition and history of an area provides data in predictive studies and would be used by others in the construction of a management plan. The methods presented here are a usable strategy in creating management plans for mangrove ecosystems. When establishing what is happening in the parks now through GIS, it is useful to have recorded information that explains

what happened in that location over time. A GIS database could be an effective part of a management plan.

8.2 Management Plan Suggestion

The Oleta mangrove habitat is very important to the City of North Miami (DEP, 2008). It is within the Florida Statues that the objective of the Division of Recreation and Parks to "conserve these natural values for all time… in such a manner as to enable the people of Florida and visitors to enjoy these values without depleting them… to provide for the perpetual preservation of historic sites." (DEP 2018). In contrast, within the Unit Management Plan, and in the strategy recommendations by the City of Miami's Economic Development Manager, place a greater emphasis on the recreation potential rather than the preservation of natural resources (Blatt, 2018; DEP, 2008).

Mangrove forests are important ecosystems that provide many benefits to the environment as well as to humans. Mangroves preserve the wetland habitat and protect the coastline and coastal human populations (Schuerch, et al. 2018). Mangroves provide increased biodiversity, a habitat for many organisms, resources used by humans, increased water quality, a buffer from wave action and carbon sequestration (Ewel et al. 1998, Mumby et al. 2004, Nagelkerken et al. 2008, Walters et al. 2008, Kristensen et al. 2008). Wetlands, once degraded, are difficult to restore as suggested by high rates of failure in coastal wetland restorations (Palmer, 2008; Hughes & Paramor, 2004; Williams & Orr, 2002; Williams & Faber, 2001; all as cited in Moffett et al., 2015). Therefore, this mangrove population needs to be considered in a carefully executed coastal zone management plan.

Oleta management's current goals align with the restoration and conservation of their mangrove communities (DEP, 2008). The park management is interested in surveys on the local vegetation to note changes which are occurring. Mangroves are mentioned frequently; their persistence and restoration are of great importance to the ecosystem and park management. However, there is not a plan for landward migration in place.

Coastal Zone Management Plans have been successful in providing sustainability for mangrove populations in the past (Schuerch, et al., 2018). Suggestions for the management of this area to help conserve the mangrove population at Oleta were given upon review of this data. There are many factors to consider when developing a coastal zone management plan including

stakeholders, environmental integrity, human populations, uncertainties, adaptability, and economics (Nicolls et al., 2013). Developing a management plan requires multiple parties to form committees, have meetings, educate the public, agree upon goals and the decision-making process for when analyzing various project proposals (Nicolls et al., 2013; Peyronnin et al., 2013).

The elimination of stress not directly related to climate change will help assist in increasing the health, and therefore the resilience, of this population. Stress such as high boating activity, invasive species (particularly the Australian pine invasion), and pollution need to be addressed. The Friends' of Oleta River State Park host cleanups, invasive species removal, and dune planting (https://friendsofoletariverstatepark.org/). Their efforts should be supplemented through projects developed within a comprehensive park management plan.

A plan for the mangrove ecosystem's persistence through sea level rise needs to be added to the current Oleta management plan. Measures in the plan for mangrove resilience will need to be implemented and modified as needed to best support this habitat during sea level rise. Combining historic knowledge of how the mangrove population has changed within Oleta through field assessments to determine the current state of the coastal area along with land use data will provide valuable information critical to the conservation and preservation of these mangroves and the ecosystem they support.

It is important to conduct studies which predict the response of local mangrove communities under different sea level and climate change scenarios. Local monitoring of the mangrove communities' response and landward migration is needed due to the uncertainties associated with climate change and the rate of sea level rise. Developments and roadways will need to be abandoned to provide inland space, as sea level would floods these areas regardless. The process of providing accommodating space is less studied and more research should be done on this (Schuerch, et al. 2018). As with any other important environmental issue, the public should be educated. The public needs to be informed about the importance of mangroves (for the environment as well as ecosystem services) to reduce damage done on mangroves by people, encourage the public to contact policymakers in regards of protecting and enhancing local mangroves, and to hopefully persuade people to take steps in reducing their carbon footprint in efforts to mitigate future climate change.

It would be a useful future project to use the classification tool in ArcGIS to reclassify the various tree areas using the automated program. This would allow for a more accurate land cover analysis eliminating risk of human error. Another idea for future research would be to analyze the rate of the Australian pine invasion and shoreline loss to determine how quickly these stressors are making an impact. Additionally, there is a useful software called Visual_HEA: Habitat Equivalency Analysis which can calculate the value associated with natural resource damage (Kohler & Dodge, 2006). This program could be applied to Oleta to determine the amount of habitat restoration required for the loss of habitat which has already occurred.

The City of North Miami should develop a management plan in a similar manner to the one developed by the state of Louisiana for their coastal environment. This plan would need to include the participation of all stakeholders relative to Oleta and needs to be a public involved process. Goals should include a plan for inland migration, invasive species management and pollution management.

9. Works Cited

Alongi, D. M. (2008). Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science, 76*(1), 1-13.

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

Bezona, N., Hensley, D., Yogi, J., Tavares, J., Rauch, F., Iwata, R., . . . Clifford, P. (2009). Salt and Wind Tolerance of Landscape Plants for Hawai'i.

Blasco, F., Aizpuru, M., & Gers, C. (2001). Depletion of the mangroves of Continental Asia. *Wetlands Ecology and Management, 9*(3), 255-266.

Blatt, S. (2018). *Strengthening North Miami's Ties to Oleta River State Park*.

Bragg, D. C., Frelich, L. E., Leverett, R. T., Blozan, W., & Luthringer, D. J. (2011). The sine method: An alternative height measurement technique. *Research Note SRS-RN-22. Asheville, NC: USDA-Forest Service, Southern Research Station. 12 p., 22*, 1-12.

Cahoon, D. R., Hensel, P. F., Spencer, T., Reed, D. J., McKee, K. L., & Saintilan, N. (2006). Coastal wetland vulnerability to relative sea-level rise: wetland elevation trends and process controls. In *Wetlands and natural resource management* (pp. 271-292): Springer.

Cohen, M. C. L., Behling, H., & Lara, R. J. (2005). Amazonian mangrove dynamics during the last millennium: The relative sea-level and the Little Ice Age. *Review of Palaeobotany and Palynology, 136*(1-2), 93-108. doi:10.1016/j.revpalbo.2005.05.002

Cohen, M. C. L., & Lara, R. J. (2003). Temporal changes of mangrove vegetation boundaries in Amazonia: application of GIS and remote sensing techniques. *Wetlands Ecology and Management, 11*(4), 223-231.

Cutshaw, S. A. (2017). *Economic Impact Assessment - Florida State Park System*. Retrieved from https://floridadep.gov/sites/default/files/Economic%20Impact%20Assessment%202016-2017.pdf

Dahdouh-Guebas, F. (2002). The use of remote sensing and GIS in the sustainable management of tropical coastal ecosystems. *Environment, Development and Sustainability, 4*(2), 93-112.

Division of Recreation and Parks. (2008). *Oleta River State Park Unit Management Plan*. State of Florida Department of Environmental Protection Division of Recreation and Parks

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature geoscience, 4*(5), 293.

Doyle, T. W., Krauss, K. W., Conner, W. H., & From, A. S. (2010). Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise. *Forest Ecology and Management, 259*(4), 770-777.

Ellison, J. C., & Stoddart, D. R. (1991). Mangrove Ecosystem Collapse during Predicted Sea-Level Rise: Holocene Analogues and Implications. *Journal of Coastal Research, 7*(1), 151-165. doi:10.2307/4297812

Engelhart, S. E., Horton, B. P., Roberts, D. H., Bryant, C. L., & Corbett, D. R. (2007). Mangrove pollen of Indonesia and its suitability as a sea-level indicator. *Marine Geology, 242*(1-3), 65-81.

Ewel, K., Twilley, R., & Ong, J. (1998). Different kinds of mangrove forests provide different goods and services. *Global Ecology & Biogeography Letters, 7*(1), 83-94.

Gilman, E., Ellison, J., & Coleman, R. (2007). Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. *Environmental Monitoring and Assessment, 124*(1-3), 105-130.

Gilman, E., Ellison, J., Duke, N. C., & Field, C. (2008). Threats to mangroves from climate change and adaptation options: a review. *Aquatic Botany, 89*(2), 237-250.

Godoy, M. D. P., & De Lacerda, L. D. (2015). Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution. *Anais da Academia Brasileira de Ciências, 87*, 651-667. Retrieved from http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0001-37652015000200651&nrm=iso

Harlem, P. (1979). Aerial photographic interpretation of the historical changes in northern Biscayne Bay, Florida: 1925 to 1976. Sea Grant Tech. *Bull*(40), 151.

IPCC, W. (2013). IPCC, 2013: summary for policymakers. *Climate change*.

Kirui, K. B., Kairo, J. G., Bosire, J., Viergever, K. M., Rudra, S., Huxham, M., & Briers, R. A. (2013). Mapping of mangrove forest land cover change along the Kenya coastline using Landsat imagery. *Ocean & Coastal Management, 83*, 19-24. doi:http://dx.doi.org/10.1016/j.ocecoaman.2011.12.004

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature, 504*(7478), 53-60.

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016). Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change, 6*(3), 253.

Kohler, K. E., & Dodge, R. E. (2006). Visual_HEA: Habitat Equivalency Analysis Software to Calculate Compensatory Restoration Following Natural Resource Injury *Marine & Environmental Sciences Faculty Proceedings, Presentations, Speeches, Lectures. 37.* . Retrieved from https://nsuworks.nova.edu/occ_facpresentations/37

Kristensen, E., Bouillon, S., Dittmar, T., & Marchand, C. (2008). Organic carbon dynamics in mangrove ecosystems: A review. *Aquatic Botany, 89*(2), 201-219. doi:http://dx.doi.org/10.1016/j.aquabot.2007.12.005

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T. V., & Dech, S. (2011). Remote sensing of mangrove ecosystems: A review. *Remote Sensing, 3*(5), 878-928.

Lejeune, J.-F. (2010). Interame: Miami and the Pan-American Dream. *South Florida History*. Retrieved from https://web.archive.org/web/20100612183743/http://www.hmsf.org/exhibits/interama/interama.pdf

Li, S., Meng, X., Ge, Z., & Zhang, L. (2015). Evaluation of the threat from sea-level rise to the mangrove ecosystems in Tieshangang Bay, southern China. *Ocean & Coastal Management, 109*, 1-8.

Lodge, T. E. (2016). *The Everglades handbook: understanding the ecosystem*: Crc Press.

Lovelock, C., Bennion, V., Grinham, A., & Cahoon, D. (2011). The Role of Surface and Subsurface Processes in Keeping Pace with Sea Level Rise in Intertidal Wetlands of Moreton Bay, Queensland, Australia. *Ecosystems, 14*(5), 745-757. doi:10.1007/s10021-011-9443-9

Marsh, G. A., & Bane, L. L. (1995). *Life Along The Mangrove Shore: A Guide To Common Estuarine Plants And Animals Of Southern Florida*. Hobe Sound, Florida: Florida Classics Library.

McKee, K. L., Cahoon, D. R., & Feller, I. C. (2007). Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography, 16*(5), 545-556. doi:10.1111/j.1466-8238.2007.00317.x

Miami-Dade County Division of Environmental Resources Management. (2007). *Preserving our Natural Resource Resilience [PowerPoint Slides]*. Retrieved from https://www.miamidade.gov/planning/library/presentations/2014-03-07-preserving-our-natural-resilience.pdf

Moffett, K., Nardin, W., Silvestri, S., Wang, C., & Temmerman, S. (2015). Multiple Stable States and Catastrophic Shifts in Coastal Wetlands: Progress, Challenges, and Opportunities in Validating Theory Using Remote Sensing and Other Methods. *Remote Sensing, 7*(8), 10184-10226. doi:10.3390/rs70810184

Mumby, P. J., Edwards, A. J., Ernesto Arias-Gonzalez, J., Lindeman, K. C., Blackwell, P. G., Gall, A., . . . C. Llewellyn, G. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature, 427*, 533+. Retrieved from https://www.nature.com/articles/nature02286

Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., . . . Somerfield, P. J. (2008). The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquatic Botany, 89*(2), 155-185. doi:http://dx.doi.org/10.1016/j.aquabot.2007.12.007

Natural Storage Areas. (n.d.). Retrieved from https://www.northmiamifl.gov/313/Natural-Storage-Areas

Nicholls, R., Townend, I., Bradbury, A., Ramsbottom, D., & Day, S. (2013). Planning for long-term coastal change: experiences from England and Wales. *Ocean Engineering, 71*, 3-16.

Noble, C. V., Drew, R. W., & Slabaugh, J. D. (1996). *Soil survey of Dade county area, Florida*: The Service.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., . . . Dasgupta, P. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*: Ipcc.

Paine, D., & Kiser, J. (2003). Aerial photography and image interpretation. In: John Wiley and Sons, Inc., Hoboken, New Jersey, USA.

Parkinson, R. W., DeLaune, R. D., & White, J. R. (1994). Holocene sea-level rise and the fate of mangrove forests within the wider Caribbean region. *Journal of Coastal Research*, 1077-1086.

Peyronnin, N., Green, M., Richards, C. P., Owens, A., Reed, D., Chamberlain, J., . . . Belhadjali, K. (2013). Louisiana's 2012 coastal master plan: overview of a science-based and publicly informed decision-making process. *Journal of Coastal Research, 67*(sp1), 1-15.

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., . . . Yong, J. W. H. (2010). The Loss of Species: Mangrove Extinction Risk and Geographic Areas of Global Concern. *PLoS ONE, 5*(4), e10095. doi:10.1371/journal.pone.0010095

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., . . . Vafeidis, A. T. (2018). Future response of global coastal wetlands to sea-level rise. *Nature, 561*(7722), 231.

Simard, M., Zhang, K., Rivera-Monroy, V. H., Ross, M. S., Ruiz, P. L., Castañeda-Moya, E., . . . Rodriguez, E. (2006). Mapping Height and Biomass of Mangrove Forests in Everglades National Park with SRTM Elevation Data. *Photogrammetric Engineering & Remote Sensing, 72*(3), 299-311. doi:10.14358/PERS.72.3.299

Spencer, T., Schuerch, M., Nicholls, R. J., Hinkel, J., Lincke, D., Vafeidis, A., . . . Brown, S. (2016). Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. *Global and Planetary Change, 139*, 15-30.

Sulong, I., Mohd-Lokman, H., Mohd-Tarmizi, K., & Ismail, A. (2002). Mangrove mapping using Landsat imagery and aerial photographs: Kemaman District, Terengganu, Malaysia. *Environment, Development and Sustainability, 4*(2), 135-152.

Swetnam, T. W., Allen, C. D., & Betancourt, J. L. (1999). Applied historical ecology: using the past to manage for the future. *Ecological Applications, 9*(4), 1189-1206.

Teas, H. J., Wanless, H. R., & Chardon, R. E. (1976). *Effects of man on the shore vegetation of Biscayne Bay*: University of Miami Sea Grant Program.

The Ramsar Convention Secretariat. (2001). *Wetland values and functions: climate change mitigation*. Gland, Switzerland Retrieved from https://www.ramsar.org/sites/default/files/documents/tmp/pdf/info/values_climate_e.pdf

Traill, L. W., Perhans, K., Lovelock, C. E., Prohaska, A., McFallan, S., Rhodes, J. R., & Wilson, K. A. (2011). Managing for change: wetland transitions under sea-level rise and outcomes for threatened species. *Diversity and Distributions, 17*(6), 1225-1233. doi:10.1111/j.1472-4642.2011.00807.x

Walters, B. B., Rönnbäck, P., Kovacs, J. M., Crona, B., Hussain, S. A., Badola, R., . . . Dahdouh-Guebas, F. (2008). Ethnobiology, socio-economics and management of mangrove forests: A review. *Aquatic Botany, 89*(2), 220-236. doi:http://dx.doi.org/10.1016/j.aquabot.2008.02.009

Xie, Z., Roberts, C., & Johnson, B. (2008). Object-based target search using remotely sensed data: A case study in detecting invasive exotic Australian Pine in south Florida. *ISPRS Journal of Photogrammetry and Remote Sensing, 63*(6), 647-660.