

# POTENTIAL RESPONSES OF CARIBBEAN MANGROVES TO SEA LEVEL RISE

Michelle Budny

## Abstract

Mangroves are woody plants that create a transitional environment between land and sea in the tropics. These plants are adapted to frequent inundation in waterlogged soils through specialized root morphology; however, sea level rise induced by climate change may affect the frequency and depth of inundation. Many studies speculate that mangrove populations will respond negatively to sea level rise, though extent of the response remains unclear given that different mangrove species possess adaptations that may help them cope with these changes in sea level. In this study, STELLA modeling software was used to simulate how long before two Caribbean species of mangroves on the coast of Belize, *Avicenna germinans* and *Rhizophora mangle*, might be affected by sea level rise. Predictions of sea level rise were used along with average coastal slope and mangrove density to model how fast both species could be affected. The model suggests *A. germinans* would be affected much slower than *R. mangle* due to its position further inland and an assumed higher critical sea level. This STELLA model provides a general baseline for negative responses of mangrove populations to sea level rise, and the next step is to augment the model by incorporating additional information about mangrove physiology and local sea level rise.

## Introduction

Mangroves are coastal ecosystems in the tropics that are important for a variety of environmental and anthropogenic reasons. They stabilize coastlines (Wright et al. 1991), slow tidal waters and accumulate sediment (Gilman et al. 2008), and provide habitat and shelter for both marine and terrestrial fauna (Blasco et al. 1996, Lee et al. 2006, Nagelkerken et al. 2008). Mangrove trees tend to grow densely intertwined which provides a forest buffer from waves and storm surges (Wright et al. 1991, Day et al. 2008). Many of the species that find refuge in mangroves as juveniles are commercially fished as adults (Louis et al. 1995) providing resources for people who live in these regions. However, these services derived from mangroves may be lost if the plants are susceptible to predicted rises in sea levels associated with anthropogenic climate change. Such sea level rise could increase inundation of roots and this excess water would decrease the capacity of mangroves to take in air, increasing physical stress. This could lead to an overall reduction in plant growth and reproduction, potentially causing a decrease in mangrove populations. Given the importance of these ecosystems, it is important to understand how they might respond to these environmental stresses. Therefore, the goal of this study is to model the potential influence sea level rise may have on mangrove populations along the coast of Belize. The results will be used as a baseline for future laboratory and field research examining how co-existing Caribbean mangrove species and their dependent fish populations might respond to changes in sea level.

### *What are mangroves?*

Mangroves are coastal ecosystems of woody plants in the tropics. These ecosystems are limited to latitudes between 30°N and 30°S (Carter 1988) due to a threshold at the 20°C seawater isotherm (Blasco et al. 1996, Duke et al. 1998). However, the plants are able to survive slightly farther south on the eastern coast of continents due to the influence of warm ocean currents (Hogarth 1999).

The more than sixty species of mangroves found worldwide can be classified into 20 genera and 16 families (Carter 1988). The wide genetic diversity suggests that mangroves evolved adaptations to coastal environments through convergence and not through a common ancestor (Hogarth 1999). The greatest species diversity is found in Southeast Asia and Australia, while only twenty percent of all species occur in North and Central America and West Africa (Carter 1988). This uneven global distribution of mangroves is explained by continental drift (Hogarth 1999). Four of the most common species in the East Atlantic are *Rhizophora mangle* (Red mangrove), *Avicenna germinans* (Black mangrove), *Laguncularia racemosa* (White mangrove), and *Conocarpus erectus* (Buttonwood mangrove) (Carter 1998, Blasco et al. 1996).

Mangroves tend to show species zonation (Carter 1988) although zonation patterns are sometimes difficult to define (Hogarth 1999). The most prominent patterns might be explained by propagule sorting in the water or salinity tolerance (Hogarth 1999), but the definite mechanisms of zonal distribution are poorly understood (Semenuik 1994). Species in the Caribbean often show a clear pattern of zonation. *R. mangle* tends to be the most dominant and is found at the edge of the coastal zone. *A. germinans* can also survive at the coastal edge, but will succeed behind *R. mangle* if it is present. Both *L. racemosa* and *C. erectus* have adaptation to tolerate some inundation, but prefer more sheltered, dry areas behind *R. mangle* and *A. germinans* (Carter 1998).

### **Adaptations to coastal environments**

Because of their coastal location, mangroves create a transitional ecotone from freshwater to saltwater environments. This means they receive freshwater inputs from precipitation, rivers,

and groundwater and receive saltwater inputs from the sea. Such conditions create an environment with nearly fluid soils and fluctuating levels of salinity. Mangroves have developed specialized adaptations to cope with these harsh habitat conditions.

### *Surviving in waterlogged soils*

The soils of mangrove environments are frequently waterlogged and provide little to no oxygen. Specialized roots help the mangrove species cope with these conditions. *Rhizophora* species sprout aerial roots from the trunk 2 m above the ground (Hogarth 1999). Also known as stilts (Hogarth 1999) or props (Carter 1998), these roots arch outward from the tree then grow down into the soil subsurface (Carter 1998, Hogarth 1999). The surface to the horizontal portion is covered with small breathing holes, called lenticels (Carter 1998, Hogarth 1999), that transport air belowground through pores within the root. Roots from adjacent *Rhizophora* trees often cross each other forming dense tangles (Hogarth 1999).

*Avicennia* species have different adaptations to water logging than those of *Rhizophora*. Instead of extending aerial roots, *Avicennia* have shallow horizontal roots with small snorkel-like extensions, pneumatophores, that stand about 30 cm tall and rise vertically from the root every 15-30 cm (Hogarth 1999). These pneumatophores are covered with lenticels (Carter 1998, Hogarth 1999), and a tree only 2-3 m tall might have more than 10,000 pneumatophores (Hogarth 1999). The shallow but wide root systems of both *Avicennia* and *Rhizophora* are effective at anchoring the trees in unstable and often fluid soils (Hogarth 1999). Other species have adaptations such as shallow snaking roots or knee roots that break the surface of the water at waving intervals (Hogarth 1999).

### *Salt Adaptations*

The salinity levels of coastal mangroves fall between that of the freshwater and saltwater inputs to which these ecosystems are subjected (Hogarth 1999). This level can vary, however, due to evaporation. Mangroves have adapted to cope with hyper saline environments through exclusion from the roots, secretion of excess salts, and tolerance (Hogarth 1999). Species including *Avicennia* exclude salt by maintaining negative hydrostatic pressure within the root to combat the negative osmotic pressure of the root environment. Through this process, water is pulled into the root, but unwanted substances are kept out.

Although root morphology helps keep salt out of the plant, some salt can still accumulate in the plant tissues (Hogarth 1999). The presence of too much salt can result in enzyme disruption. To get rid of extra salt, *Avicennia* and *Rhizophora* deposit salt on the bark of their stems and roots (Hogarth 1999). *Avicennia* species also have salt excretion glands on their leaves. Small openings release excess salt, and short hairs on the underside of the leaf wick the salt droplets away (Hogarth 1999). Leaves are often visibly coated with salt crystals (Carter 1998, Hogarth 1999).

### *Importance of mangrove communities*

Mangrove services are vital to the landscape. Their complex root structures and dense branch coverage help protect inland areas from storm surges. In addition, the stabilization of the coasts helps slow tidal water flow. Wright et al. (1991) examined the hydrology of a mangrove island near the barrier reef of Belize. A variety of field studies including transect samples, water level monitoring, and dye studies were used to survey and quantify the path and velocity of tidal flow through the mangroves on Twin Caye. The tidal flow is not smooth but follows a network of interconnected channels due to the frictional resistance of the mangroves (Wright et al. 1991). Using Manning's roughness coefficient, the velocity of tidal waters was measured along a transect line. Velocity varied between  $0.004 \text{ m s}^{-1}$  and  $0.034 \text{ m s}^{-1}$  along the study site. These variable flow patterns suggest that mangrove plays an important role in directing the flow of tidal water (Wright et al. 1991).

In conjunction with protecting the coastal landscape, mangroves provide habitat for a variety of aquatic species. Mud crab, jellyfish, echinoderm, and other fish species all find shelter among the arching root structure of the mangroves. Mud crabs burrow in the sediment accreted by the roots. Species of sponges grow on submerged portions of prop roots. The roots also provide a calm refuge for juvenile reef species such as the endangered goliath grouper (Frias-Torres and Luo 2008).

### *Community interactions*

A number of other species have important interactions with mangroves. These ecosystems are a host to a variety of fauna. Above ground, mangrove canopies attract some

migratory bird species (Lee et al. 2006), although few of these are mangrove specialists (Nagelkerken et al 2008). A few frog and reptile species are found in mangroves. The frogs are of particular interest since few amphibians are tolerant to saline environments, but little is known about these species thus far (Nagelkerken et al. 2008). Two species that have been identified are *Rana cancrivora* of Southeast Asia that preys on crabs and *Eleutherodactylus caribe*, which is the only frog known to inhabit flooded *R. mangle* habitats in the Caribbean (Nagelkerken et al. 2008).

Underwater, prop roots provide a hard substrate for sponges to grow. Prawns, crabs, and gastropods burrow in the soft sediment beneath the roots. These animals are also important to the function of mangroves. Burrowing crabs provide aeration to the roots (Nagelkerken et al. 2008). Organic leaf litter is broken down by crabs and gastropods (Lee 2008), and the nutrients are recycled. Crab and some insect species also influence the distribution of mangroves by selectively feeding on some propagules (Lee 2008).

Mangrove root structures also provide a calm environment where fish are protected from predators. Fish species feed on organic matter and benthic insects. Many of these species live in the mangroves as juveniles and migrate to the coral reefs as adults. Mumby et al. (2004) performed a comparison study between coral reefs near mangrove-rich environments and coral reefs near mangrove-scarce environments close to the barrier reef off the coast of Belize. They found that the biomass of reef fish in the mangrove-rich ecosystems was significantly greater than that of mangrove-scarce ecosystems. Biomass of most species at least doubled in mangrove-rich environments, and the biomass of *Haemulon sciurus* (bluestripped grunt) in mangroves was 25 times greater than in areas where mangroves are scarce (Mumby et al. 2004). This suggests that mangroves are a significant part of coral reef species populations. As a result, a decline in mangrove populations could negatively impact obligate reef species (Mumby et al. 2004).

One of most notable associations occurs between mangroves and *Scarus guacamia* (rainbow parrotfish), the largest herbivorous fish in the Atlantic Ocean. As a juvenile the parrotfish was found almost exclusively in mangroves. Adults were rarely found in reefs adjacent to mangrove-scarce environments. Since parrotfish eat algae that grow on coral, a decline in their population due to mangrove loss could lead to an outbreak of coral algae that might negatively impact the health of the reef (Mumby et al. 2004).

Another study (Louis et al. 1995) has demonstrated the wide range of fish species that inhabit mangrove ecosystems. To observe the number of fish living in mangroves, eight different samples were taken from locations off the coastline of Martinique Island. A net system was left in the water for twenty-four hours near mangrove habitats. A total of 87 species of fish were collected from all eight samples. Most of fish that were caught were juveniles, and no single species occurred in every sample (Louis et al. 1995). Although the overall biomass at each station was similar, species composition varied by location in order to maximize the use of the mangrove habitat (Louis et al. 1995).

### **Threats to mangroves**

Currently, human actions are both directly and indirectly threatening the future of mangrove populations. Urbanization of coastlines has led to the destruction of 3.6 million ha of mangroves worldwide from 1980 to 2005 (FAO 2007). Landscape alteration from deforestation directly reduces mangrove populations. The removal of mangroves also releases greenhouse gases into the atmosphere, exacerbating climate change. As a result, climate change could affect natural processes that influence mangrove distribution and survival. Changes in the frequency of intense storms, availability of freshwater, and mean sea level may all result from shifts in climate.

#### *Deforestation*

The biggest threat to mangrove populations is deforestation from human development. Urbanization has several implications toward mangrove communities including alterations to hydrologic systems, water quality, nutrient cycles, and sedimentation (Lee et al. 2006). Deforestation also leads to direct habitat change. Lee et al. (2006) suggest that fragmentation will lead to an increased edge effect giving invasive species better opportunities to over run the natural environment. In addition, mangrove swamps are being transformed into aquaculture ponds to raise shrimp for commercial distribution (Ronnback et al. 2003). In the wild, species such as *Penaeus mondon* (tiger shrimp) spawn at sea, and the larvae settle in coastal nurseries. Mangrove environments are the preferred nurseries of juvenile tiger shrimp because they provide food, control water quality, and minimize disturbance from storms and waves. Mangroves have

been cleared to create fifty percent of aquaculture ponds in Andhra Pradesh, India. However, the economic importance of mangrove habitats is under valued (Ronnback et al. 2003).

### *Climate change*

Although deforestation is threatening mangroves most quickly, climate change is expected to have several impacts on mangroves as well. The Intergovernmental Panel on Climate Change (2007) has reported dramatic increases in the atmospheric levels of greenhouse gases, especially carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), since the industrial revolution. For instance, CO<sub>2</sub> levels have risen from 290ppm in 1750 to 379ppm in 2005 (IPCC 2007). The addition of these greenhouse gases has resulted in a temperature increase of 0.74°C over the last century, and temperatures have continued to rise by 0.16°C per decade since 1979 (IPCC 2007).

These increases in atmospheric temperature will impact Earth's physical processes in ways that will largely affect ecosystems worldwide. Mangroves are no exception. The direct factors of climate change such as elevated atmospheric temperatures and CO<sub>2</sub> levels, however, are not expected to have as great an effect as indirect factors (Gilman et al. 2008). Changes that may negatively impact mangrove populations include increased storm activity and intensity, changes in precipitation and freshwater availability, and rises in mean sea level.

In a review by Gilman et al. (2008), the authors suggest that increases in tropical storms could result in damage to mangrove foliage and even tree mortality. An influx in storm surges may also change sediment composition by collapsing or compacting the peat substrate on which mangroves grow (Gilman et al. 2008). High wind speeds would erode coastlines (Day et al. 2008, Gilman et al. 2008) and move barrier islands (Day et al. 2008). In addition, Day et al. (2008) predict more frequent intense wind speeds would blow over more trees. Losing this coastal barrier could lead to more damage on land (Day et al. 2008).

Climate change is also expected to change global precipitation distributions. Regions between 10° S and 30° N latitude, including Central America, are expected to have a decreasing trend in precipitation over the next 30-40 years (IPCC 2007). Less precipitation near coastal areas in the tropics would increase the salinity of mangrove habitats (Wright et al. 1991, Gilman et al. 2008). Although mangroves are adapted to survive in saline environments, the plants could experience reduced growth and seedling survival if freshwater from groundwater or precipitation runoff becomes less available (Gilman et al. 2008). Higher levels of salt also might lead to more



sulfate in the water, promoting anaerobic peat decomposition which would make associated mangroves more vulnerable (Gilman et al. 2008).

### *Sea level rise*

Sea level rise from climate change is expected to have the largest impact on mangrove ecosystems (Alongi 2007). Climate change may influence rises in sea level through two main processes, melting of the polar ice caps, including the break-up of glaciers and permanent ice sheets, and thermal expansion of the seawater itself. Increasing global temperatures are melting polar ice sheets at an alarming 2.7% per decade (IPCC 2007). The addition of this extra melt water causes sea levels to rise. In addition, thermal expansion contributes to sea level rise. Just as an intensified greenhouse effect causes atmospheric temperatures to rise, sea water temperature increases as well. As the water gets warmer the volume of the sea expands from increased molecular movement. Gregory and Lowe (2000) used coupled atmosphere-ocean general circulation models to predict sea level rise over the next century. With the model they project that between 1990 and 2100, average sea level will increase by 0.44-0.48 m. Thermal expansion will account for sixty percent to the change (Gregory and Lowe 2000). However, these changes will not be uniform around the globe. Geographic differences were also calculated by Gregory and Lowe (2000) relative to local topography and possible changes in atmospheric pressure. The model measured a range in variation of no change in sea level in some areas to 0.77 m in places like Japan, almost double the predicted global average (Gregory and Lowe 2000).

Since mangroves inhabit coastal areas, they have a close relationship with sea level. Of any other factor associated with climate change, rises in sea level may have the greatest influence on mangrove communities. Shifts in sea level could affect the health and position of mangroves by changing the length of root inundation, accelerating erosion, weakening root structures, and increasing the salinity of the environment (Gilman et al. 2008). Populations most vulnerable to sea level rise are those located on carbonate islands with little nutrient or sediment inputs (Gilman et al. 2008) such as the islands in the Caribbean Sea and Pacific Ocean (Alongi 2007). These islands also have low tidal ranges (Nicholls et al. 1999), so even small changes in local sea level could have major impacts on coastal environments (Semeniuk 1994).

## Potential mangrove responses to sea level rise

Mangroves may respond to sea level rise a variety different ways. The three major possible responses include landward migration away from the coast, vertical accretion of sediment above sea level, or permanent inundation of root possibly causing damage or tree mortality. Such responses will largely depend upon the rate of local sea level rise, availability of sediment and nutrients, and coastal geomorphology among other factors.

### *Migration*

Some studies suggest that mangroves will simply retreat landward (Semenuik 1994). By using aerial photographs of King Sound, Australia, Semenuik (1994) described the pattern of migration from the coast by mangrove seedlings. King Sound is an estuarine-deltaic gulf surrounded by a muddy tidal flat. The shoreline is eroding naturally at 1-3 cm yr<sup>-1</sup> (Semenuik 1994), which mimics the effect of sea level rise. As the coastal flat erodes, mangroves colonize the newly available habitat landward. This suggests that as sea level rises in an area with geomorphology similar to King Sound, mangrove populations are expected to respond by moving inland (Semenuik 1994).

A similar pattern of migration was observed in King Bay populations. Due to zonation differences, however, populations of one species may encroach on another (Semenuik 1994). A seaward *Avicennia* zone, and middle *Rhizophora* zone, and another landward zone of *Avicennia* characterize King Bay. Over a ten-year period of observation, Semenuik (1994) reported an encroachment of *Rhizophora* 1.0 m upslope into the landward *Avicennia* zone. This suggests that some species may adjust to rising sea level through migration better than others (Semenuik 1994).

Sea level rise may also provide opportunities for mangroves to migrate into other ecosystems. Doyle (2003) used a coupled spatially explicit model SELVA-MANGRO to predict changes in mangrove populations of the Florida Everglades. The SELVA model defines the habitat, water level, and salinity of an area and calculates the probability of disturbances from lightning, hurricane, or sea level rise. The MANGRO model replicates the growth, establishment, and death of trees in neo-tropical intertidal forests to predict tree gap replacement. The coupled model suggests that as sea level rise displaces freshwater swamp and marsh ecosystems, mangroves will have the opportunity to invade these areas (Doyle 2003).

Due to anthropogenic and geographic barriers, however, mangrove forests cannot always move back to optimal distances from the water. Habitats that are subjected to this “coastal squeeze” (Nicholls et al. 1999) of the encroaching ocean on one side and land or human development barriers on the other provide limited opportunities for mangrove community migration.

#### *Accretion greater than sea level rise*

If the species is susceptible to decline from increase flooding as suggested by several studies (Ellison and Farnsworth 1997, Nicholls et al. 1999, Krauss et al. 2008) it may have a chance to “escape” sea level rise by increasing elevation of the coastal sediment above mean sea level (Field 1995, Alongi 2007). Although the mangroves have the ability to trap the sediment, accretion rates also depend on the coastal availability of particulate matter (Field 1995, Nicholls et al. 1999). Typically, more sediment is available in estuarine mangrove habitats where rivers transport particulates, and less is available on small islands with no river inputs and low tidal variation (Semeniuk 1994).

One factor that may influence accretion rates is the availability of nutrients in the environment. The acquisition of abundant nitrogen and phosphorus nutrients could lead to an increase in the production of root biomass, improving the ability to collect sediment. McKee et al. (2007) manipulated peat formation of mangrove sites in Belize by adding nitrogen and phosphorus in the form of urea or superphosphate. The effects of these added nutrients were measured by using a rod-surface elevation table and by radiocarbon dating sediment cores. Results showed a decrease in elevation in areas with low nutrients and root mass and an increase in elevation where root mass was higher (McKee et al. 2007). Based on their results, McKee et al. (2007) suggest that without adequate nutrient inputs for root production, mangroves forests will become submerged as sea level rises.

#### *Accretion less than sea level rise*

If these potential adaptation methods are not realized, mangrove forests may drown from increased inundation of the roots due to sea level rise. Even through wetlands are submerged for

part of the day from diurnal tide cycles (Nicholls et al. 1999), lengthened periods of flooding could result in reduced growth and eventually death from water logging (Ellison and Farnsworth 1997, Nicholls et al. 1999, Krauss et al. 2008). In a lab study lasting 2½ years, Ellison and Farnsworth (1997) measured the growth response of *R. mangle* propagules to high water (+16 cm), low water (-16 cm), and mean water treatments based on climate projections over the next 50 - 100 years. Measurements of stem diameter, plant height, branch length, total number of leaves and flowers, and leaf thickness, area, and chlorophyll compositions were used to assess each plant's growth. Propagules that had been collected from Belize and grown in pots in hydroponic tanks were found to grow slower under high water condition than mean and low water treatments. Initially, plants in the low water treatments grew fastest, but the development of these plants eventually slowed. Plants subjected to mean water had 20% more branches and 10% more leaves than low water plants (Ellison and Farnsworth 1997). Ellison and Farnsworth (1997) conclude that even through Caribbean mangroves are able to adapt to changes less than 8-9 mm per year, larger changes in sea level could lead to the decline or, more severely, the collapse of mangrove ecosystems.

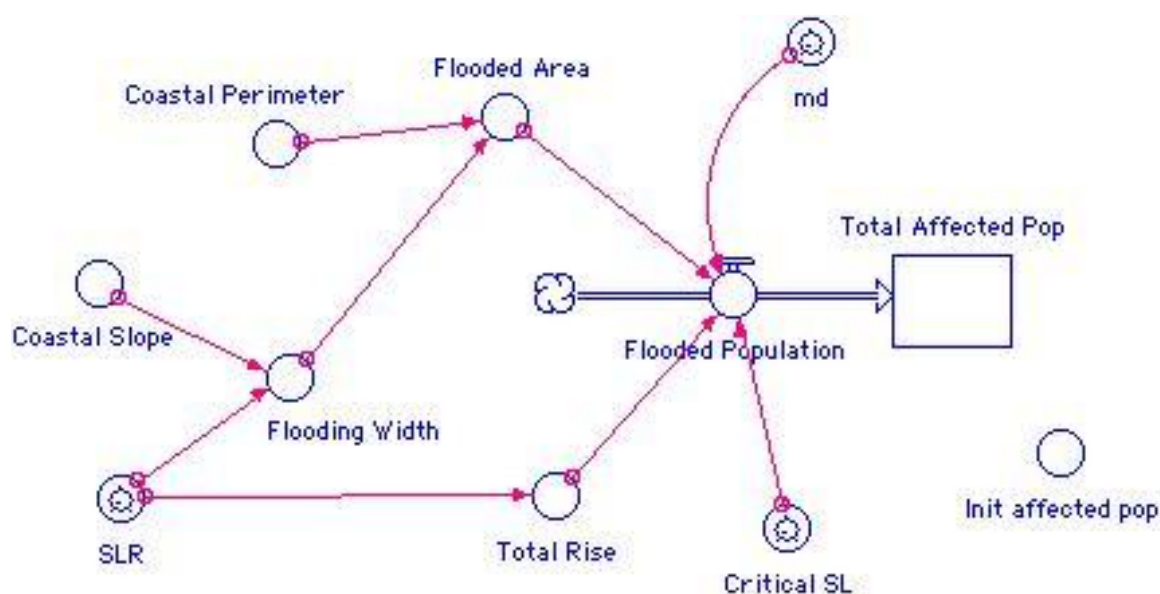
Each species must be considered when predicting mangrove response to sea level rise. He et al. (2007) found that different species have different tolerances to increased flooding. Using artificial platforms constructed in the Beibu Gulf of China and covered with substrate from the local intertidal flat, seedlings of four species were established. Eight different tidal flat elevation conditions were created on each platform to simulate changes in sea level. After one year of measurements, they found significant differences. Based on measurements of seedling survival, stem height, leaf scar, number of leaves, and leaf area, He et al. (2007) found *Aegiceras corniculatum* and *Avicennia marina* to be more tolerant overall to sea level rise than *Bruguiera gymnorrhiza* and *Rhizophora stylosa*. These changes suggest that community compositions could change with respect to sea level rise (Alongi 2007).

Given the variety of possible responses of mangroves to sea level rise, it is important to observe the interaction of mangrove communities with environmental conditions. The goal of this study is to model mangrove populations of coastal Belize and their potential responses to sea level rise. The two most dominant species in Belize, *A. germinans* and *R. mangle*, will be considered based on their physiological limitations in conjunction with projected rates of sea

level rise. The outcome of the model will serve as the basis for future research of changes to mangrove community composition due to rises in sea level.

## Methods

In order to simulate how sea level rise might change community compositions of *A. germinans* and *R. mangle* in Belize, STELLA modeling software was used (Figure 1). Values from the IPCC Report (2007) were used to calculate sea level rise. Both the average observed rate of  $1.7 \text{ mm yr}^{-1}$  and the high-end estimate of  $4.0 \text{ mm yr}^{-1}$  were considered. Sea level rise and the average coastal slope of  $1^\circ$  were used to calculate the flooded width of the coast. The flood width is then multiplied by the coastal perimeter of Belize, 386 km, to find the flooded area. The population of the flooded area is found by multiplying the flooded area by the average population density for both species of mangroves as found by Proffitt and Devlin (2005). Population density was defined for *A. germinans* as  $1 \text{ m}^{-2}$  and for *R. mangle* as  $2 \text{ m}^{-2}$  (Proffitt and Devlin 2005). The model only returned the flooded population as an affected population when total sea level rise reached a critical sea level value for each species. Since the roots of these trees are morphologically different, the model assumes that they will react differently to sea level rise as breathing lenticels become submerged. A critical value of 300 mm, the average height of pneumatophores (Hogarth 1999), was chosen for *A. germinans*, and a critical value of 160 mm was chosen for *R. mangle* based on the measurements of Ellison and Farnsworth (1997).



**Figure 1: STELLA model**

The model was run at both  $1.7 \text{ mm yr}^{-1}$  and  $4.0 \text{ mm yr}^{-1}$  rates of sea level rise for both species (IPCC 2007). Total sea level rise over time was returned. These measurements were then used to calculate how long before mangrove populations were impacted based on the critical sea level value for both species. The model also returned how many trees might be affected after the critical sea level value was reached. The model assumes that the mangrove population does not have the opportunity for landward migration or vertical accretion. Newly established plants are also not considered. The coastline is assumed to be uniformly affected by sea level rise. In addition this model assumes that both species are evenly distributed along the entire length of the coast by their respective average population densities.

**Results***Simulation of  $1.7 \text{ mm yr}^{-1}$  sea level rise*

The model was run for *A. germinans* and *R. mangle* with critical sea level values of 300 mm and 160 mm respectively. Values for the simulation of  $1.7 \text{ mm yr}^{-1}$  sea level rise are presented in Table 1. This simulation implied that the critical level for *A. germinans* would be reached after 176.5 years, and sea level would reach the critical level for *R. mangle* after 94.1 years (Figure 2). At these times, the flood width would encroach inland 176.5 m to reach the critical value for *A. germinans* and 94.1 m inland when the critical value for *R. mangle* is reached. A map of the flooding extent can be found in the Appendix. If sea level continues to rise at a constant rate of  $1.7 \text{ mm yr}^{-1}$  after the critical values are reached, higher sea levels could affect 37,599 *A. germinans* trees and 75,198 *R. mangle* trees each year (Figure 3).

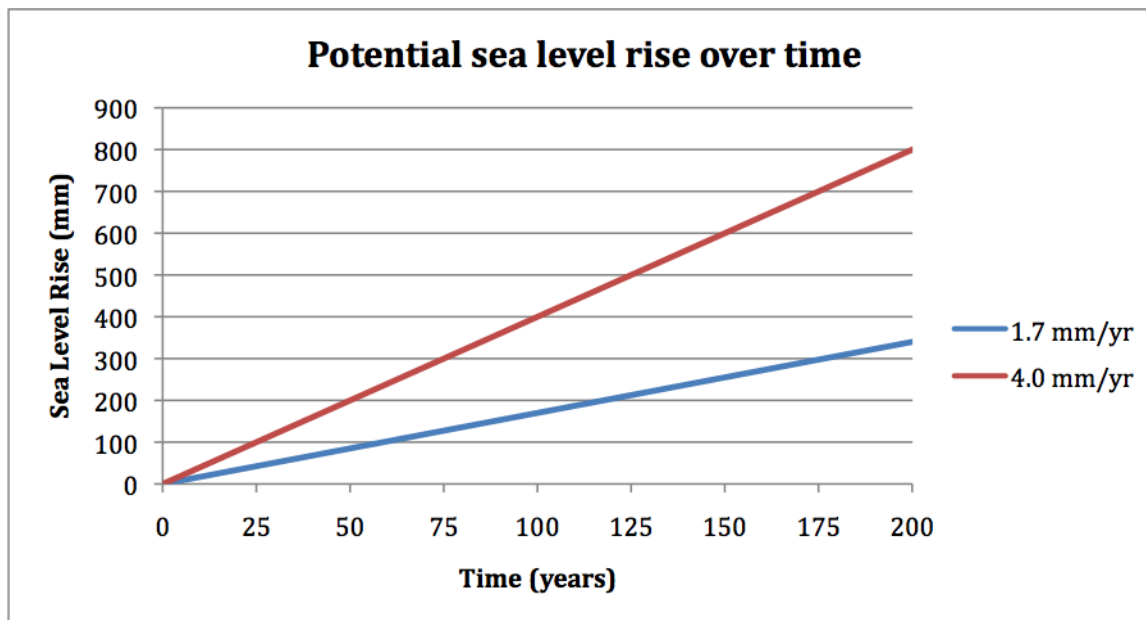


Figure 2: Potential total sea level rise over time for rates of 1.7 mm yr<sup>-1</sup> and 4.0 mm yr<sup>-1</sup>

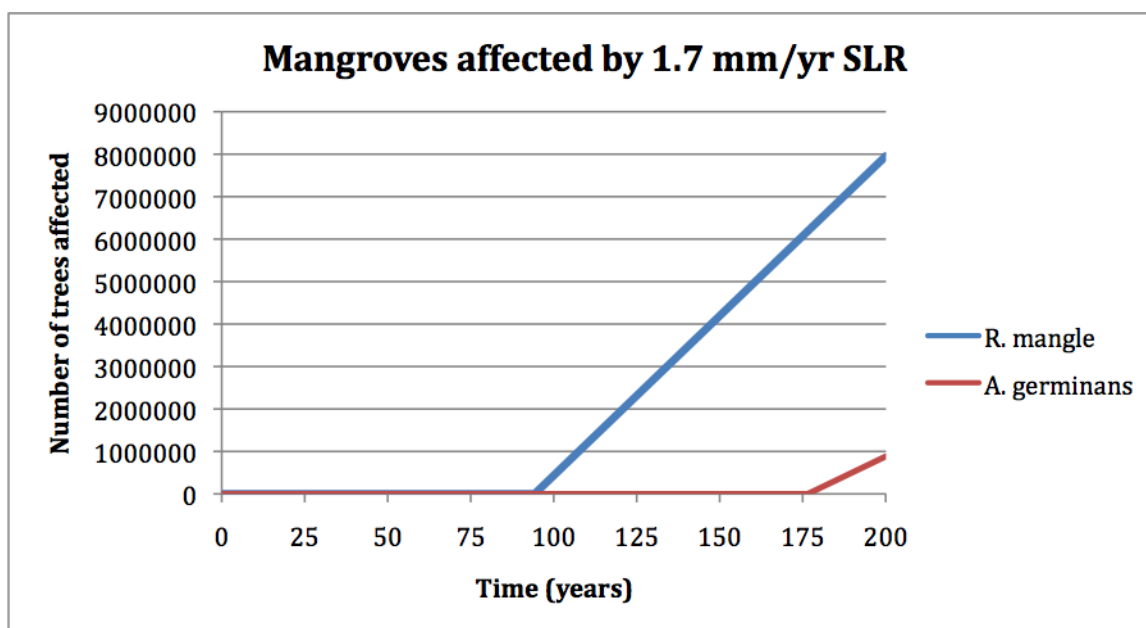


Figure 3: Number of *R. mangle* and *A. germinans* trees that could be affected as sea level rises at a rate of 1.7 mm yr<sup>-1</sup>

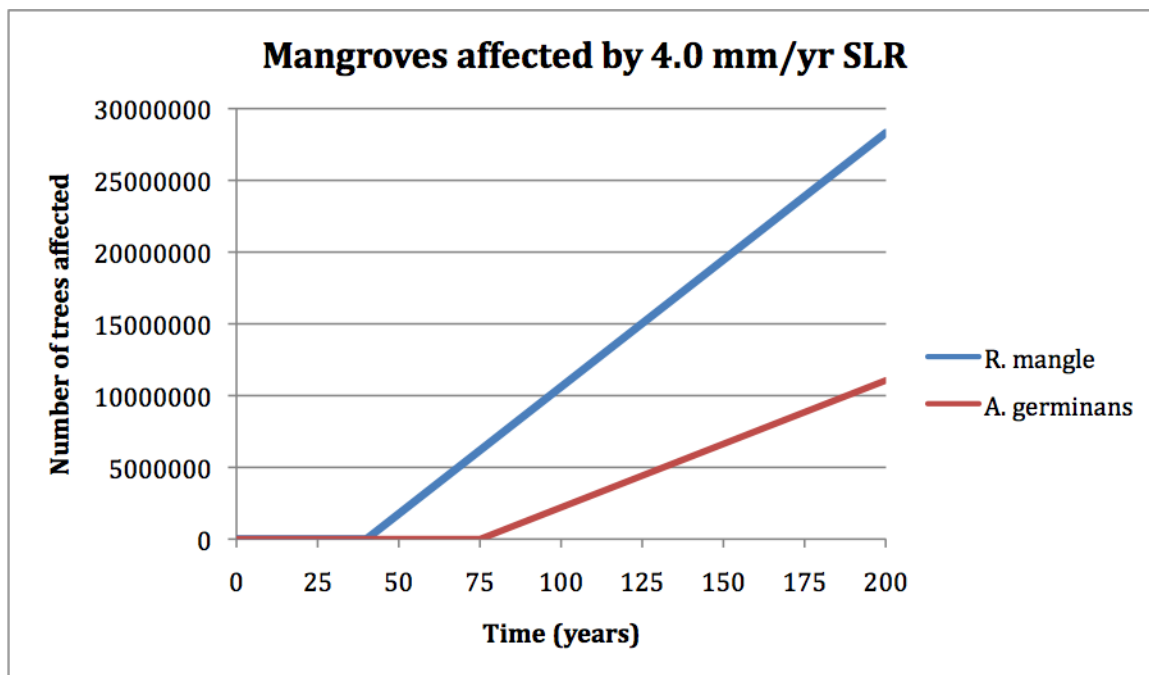
Table 1: Outcome of running model at 1.7 mm yr<sup>-1</sup>

1.7 mm yr <sup>-1</sup>	<i>A. germinans</i>	<i>R. mangle</i>
Critical sea level	300 mm	160 mm
Time to reach critical level	176.5 yrs	94.1 yrs

Flood width	176.5 m	94.1 m
Trees affected in first year	37,599	75,198

*Simulation of 4.0 mm yr<sup>-1</sup> sea level rise*

Using the model to simulate a sea level rise rate of 4.0 mm yr<sup>-1</sup> showed that it would take 75.0 years for sea level to reach the critical value of 300 mm for *A. germinans* and 40.0 years to reach the critical value of 160 mm for *R. mangle* (Figure 2). The coastal width of the flooded area would reach 172.5 m inland to reach the critical value for *A. germinans* and 92.0 m inland to reach the critical value for *R. mangle*. The number of trees affected by rising sea levels would increase yearly by 88,469 for *A. germinans* and 176,938 for *R. mangle* if the rate of 4.0 mm yr<sup>-1</sup> remains constant (Figure 4). Values for the 4.0 mm yr<sup>-1</sup> simulation are presented in Table 2.



**Figure 4:** Number of *R. mangle* and *A. germinans* trees that could be affected as sea level rises at a rate of 4.0 mm yr<sup>-1</sup>

**Table 2:** Outcome of running model at 4.0 mm yr<sup>-1</sup>



4.0 mm yr <sup>-1</sup>	<i>A. germinans</i>	<i>R. mangle</i>
Critical sea level	300 mm	160 mm
Time to reach critical level	75 yrs	40 yrs
Flood width	172.5 m	92.0 m
Trees affected in first year	88,469	176,938

## Discussion

### *Explanation of patterns*

Under simulations of both 1.7 mm yr<sup>-1</sup> and 4.0 mm yr<sup>-1</sup>, *R. mangle* will be affected sooner than *A. germinans* due to a lower critical sea level value. Since the density of *R. mangle* is greater than *A. germinans*, *R. mangle* populations could potentially decline before *A. germinans* is affected. Assuming an ecosystem where *R. mangle* and *A. germinans* are evenly distributed by average density along the entire coast, this could result in a shift not only in mangrove populations, but also in the diversity of other plant and animal species in the community that are obligate to mangroves. Species associated with *R. mangle* may decline allowing more *A. germinans* associates to inhabit the area. As sea level continues to increase, though, *A. germinans* individuals and obligates may decline as well.

### *Critique of the model*

Although the STELLA model provides baseline predictions of the possible impact of sea level rise, the complexities associated with mangrove ecosystems are not expressed. The model offers an extreme generalization of a real mangrove habitat. It assumes that local rates of sea level rise in the Caribbean Sea are equal to global averages. However, regional changes of sea level may differ from these average measurements, which could alter the time before inundation affects mangroves. In a scenario where regional sea level is actually decreasing, mangrove populations may have the opportunity to migrate toward the sea. Establishing protocol for more precise local measurements of sea level would provide better estimates for future changes in sea level and ultimately lead to more accurate predictions of the influence sea level rise could have on mangroves in Belize as well as other locations.

Topographical and distributional differences in the landscape are also not accounted for in the model. The model expresses average coastal slope as 1°, but variability in the slope will change the width of the coastal flood plain. Steeper slopes will reduce the inland extent of

flooding from sea level rise, and could provide more protection for upslope mangroves than more gentle slopes. Since *A. germinans* tends to grow in a more landward zone when *R. mangle* is present, steeper slopes could benefit *A. germinans* and lengthen the time between the impacts of sea level on the two species.

Basic characteristics about the two species were used to model their potential responses to sea level rise. However, the response of either species likely will not be linear as the model suggests. Physiological root adaptations of mangroves such as prop roots, pneumatophores, and lenticels (Carter 1988, Hogarth 1999) allow tolerance to periodic inundation of the roots. The threshold of this tolerance is not certain. Further more, the tolerance threshold may differ depending not only on the depth of inundation, but also the rate at which the depth increased. If sea level rise does not meet these thresholds, mangroves in Belize may still have the ability to migrate horizontally or vertically from sea level rise if proper habitat, sediment, and nutrient resources are available.

### **Field experiments that would improve model estimates**

Little is known about the specific physiological responses of different mangrove species to prolonged periods of root inundation. Therefore, more in depth research of these environments is necessary. Because mangrove forests serve as erosion control and impact commercial fisheries, which are the source of income for many Caribbean people, this research would have impacts beyond basic science by providing education and outreach to communities living near these precious ecosystems.

In order to address the tolerance of both *A. germinans* and *R. mangle* to sea level rise, a simulation experiment could be performed in the lab using methods described by Ellison and Farnsworth (1997). Mangrove seedlings would be gathered from selected field sites and established in pots under optimal soil, light, and temperature conditions. After the propagules have developed in maturity, they would be transplanted and separated into groups receiving different sea level treatments. The control group would experience water levels matching current field conditions, while the treatment groups will represent the range of expectations based on previous research. Growth and root architecture would be monitored until plants reach reproductive maturity in approximately two years (Ellison and Farnsworth 1997). At the end of that time, plants would be harvested and root:shoot ratios would be analyzed, as well as root

structures. Subsets of these plants may also be harvested at intermediate dates to observe progress and potential changes in growth pattern. Root biomass would be expected to decline and root architecture would be expected to shift with increasing sea level for both species. If root biomass and architecture do indeed change with increased water level, then this could suggest that accretion rates may change as well. The implication may be that species with low root biomass would have lower accretion rates and would be more likely to decline.

Linking root architecture with accretion rates in the field might require placing rod surface elevation tables (RSET) in areas containing different dominant mangrove species (McKee et al. 2007). Quantifying accretion rates using RSET measurements could help develop a better understanding of the biological controls of coastal stability. In addition, in each of these areas, root architecture could also be assessed by using minirhizotron methods. Using this method, mangrove roots would be digitally imaged using a minirhizotron camera extended through clear tubes established in the substrate. This technique could provide a reference of root architecture in actual field conditions. Execution of these methods might be difficult, however, because the tubes may not remain stationary in the soils that are often fluid.

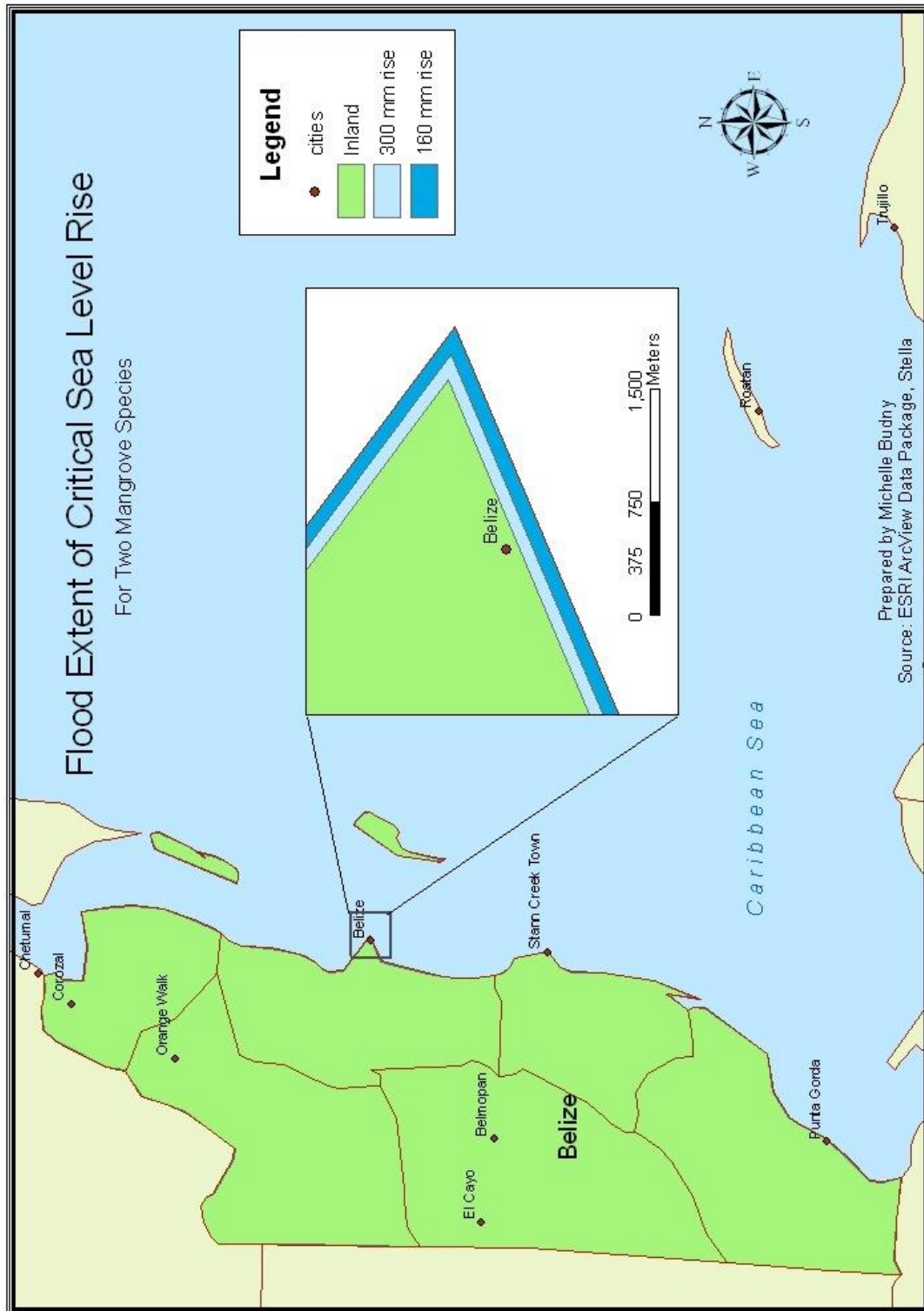
If the root architecture of one mangrove species is more susceptible to sea level rise than another, potential shifts in mangrove diversity could result in a change in associated fish populations as well. Because mangrove roots offer haven for many juvenile coral reef and commercially harvested fish species, field measurements could potentially assess fish communities using stationary net traps several times per year (Louis et al. 1995). A qualitative analysis of species diversity in mangrove ecosystems would provide a better understanding of how the community functions as a whole and what large-scale changes might occur as a result of sea level rise.

Approaching these questions systematically could uncover valuable findings regarding the function of mangrove communities. These findings would improve the accuracy of models, and a broader perspective of the impact sea level rise may have on mangrove population could be projected. Results would not only provide meaningful estimates for the future of mangrove species populations, but also for other associated plant and animal species. Understanding the importance of the mangrove ecosystem for both natural and human resources and how the ecosystem functions as a whole may improve efforts towards the conservation of mangrove forests.

**Conclusion**

Impending sea level rise could have detrimental impacts on coastal mangrove ecosystems. Changes to ecosystems like those in the Caribbean could occur in less than 100 years. However, little is known about the specific responses of mangrove physiology to higher sea levels or the role root architecture might play in these responses. Continuing to study these plants in both lab and field experiments is necessary to provide a better understanding of their life history. Combining this new information with improvements in local monitoring for changes in sea level would enhance the accuracy of future models. As a result, the model would provide better prediction of the potential response of mangrove ecosystems to sea level rise.

**Appendix:** Map of inland flood extent if sea level reaches the critical value for *A. germinans* (300 mm) and *R. mangle* (160 mm).



## References

- Alongi, D. M. (2007). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*. 76, 1-13.
- Blasco, F., Saenger, P., & Janodet, E. (1996). Mangroves as indicators of coastal change. *Catena*. 27, 167-178.
- Carter, R. W. G. (1988). *Coastal environments*. Academic Press.
- Day, J. W., Christian, R. R. , Boesch, D. M., Yáñez-Arancibia, A., Morris, J., & Twilley, R. R. (2008). Consequences of climate change on the ecogeomorphology of coastal wetlands. *31*, 477-491.
- Doyle, T. W. (2003). Predicting future mangrove forest migration in the Everglades under rising sea level. USGS Fact Sheet FS-030-3.
- Duke, N. C., Ball, M. C., & Ellison, J. C. (1998). Factors influencing biodiversity and distributional gradients in mangroves. *Global Ecology and Biogeography Letters*. 7, 27-47.
- Ellison, A. M., & Farnsworth, E. J. (1997). Simulated sea level change alters anatomy, physiology, growth, and reproduction of red mangrove (*Rhizophora mangle* L.). *Oecologia*. 112, 435-446.
- Field, C. D. (1995). Impact of expected climate change on mangroves. *Hydrobiologia*. 295, 75-81.
- FOA (2008). *The world's mangroves 1980-2005*. FAO Forestry Paper – 153.
- Frias-Torres, S., & Luo, J. (Online: 2008). Using dual-frequency sonar to detect juvenile goliath grouper *Epinephelus itajara* in mangrove habitat. *Endangered Species Research*. 1-6.
- Gilman, E. L., Ellison, J., Duke, N. C., & Field, C. (2008). Threats to mangroves from climate change and adaptation options: A review. *Aquatic Botany*, 89, 237-250.
- Gregory, J. M., & Lowe, J. A. (2000). Predictions of global and regional sea-level rise using AOGCMs with and without flux adjustment. *Geophysical Research Letters*. 27, 3069-3072.
- He, B., Lai, T., Fan, H., Wang, W., & Zheng, H. (2007). Comparison of flooding-tolerance in four mangrove species in a diurnal tidal zone in the Beibu Gulf. *Estuarine, Coastal and Shelf Science*. 74, 254-262.
- Hogarth, P. J. (1999). *The biology of mangroves*. New York: Oxford University Press.

- IPCC (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.
- Krauss, K. W., Lovelock, C. E., McKee, K. L., López-Hoffman, L., Ewe, S. M. L., & Sousa, W. P. (2008). Environmental drivers in mangrove establishment and early development: A review. *89*, 105-127.
- Lee, S. Y. (2008). Mangrove macrobenthos: Assemblages, services, and linkages. *Journal of Sea Research*. *59*, 16-29.
- Lee, S. Y., Dunn, R. J. K., Young, R. A., Connolly, R. M., Dale, P. E. R., & Dehayr, R. (2006). Impact of urbanization on coastal wetland structure and function. *31*, 149-163.
- Louis, M., Bouchon, C., & Bouchon-Navaro, Y. (1995). Spatial and temporal variations of mangrove fish assemblages in Martinique (French West Indies). *Hydrobiologia*. *295*, 275-284.
- 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*, 545-556.
- Mumby, P. J., Edwards, A. J., Arias-González, J. E., & Lindeman, K. C. (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Letters to Nature*, *427*, 533-536.
- Nagelkerken, I., Blaber, S. J. M., Bouillon, S., & Green, P. (2008). The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquatic Botany*, *89*, 155-185.
- Nicholls, R. J., Hoozemans, F. M. J., & Marchand, M. (1999). Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. *Global Environmental Change*. *9*, S69-S87.
- Semeniuk, V. (1994). Predicting the effect of sea-level rise on mangroves in Northwestern Australia. *Journal of Coastal Research*. *10*, 1050-1076.
- Rönnbäck, P., Troell, M., Zetterstrom, T., & Babu, D. E. (2003). Mangrove dependence and socio-economic concerns in shrimp hatcheries of Andhra Pradesh, India. *Environmental Conservation*, *30*, 344-352.
- Wright, R. M., Urish, D. W., & Runge, I. (1991). The hydrology of a Caribbean mangrove island. In: Cambers, G (Ed.). (1991). *Coastlines of the Caribbean*. New York: American Society of Civil Engineers.