

## Chapter 12

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# Modeling Mangrove Forest Migration Along the Southwest Coast of Florida Under Climate Change

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### Summary

Mangrove forests dominate in the intertidal zones of the tropical extent of the coast about the Gulf of Mexico, USA. Global climate change forecasts suggest that these coastal forests will be among those ecosystems most immediately threatened by projected increases in sea level and hurricanes. The interactive effects of environmental conditions that prevail in these forests and the changes that are likely to occur in a global warming climate may lead to major shifts in forest composition, structure, and function of mangrove ecosystems. The low-lying Everglades of Florida are particularly vulnerable to frequent tropical storm strikes and impending sea-level rise projected with climate change. Mangrove forests are susceptible to storm damage from wind and surge forces sufficient to alter forest structure and recovery. Computer simulation models of mangrove forest dynamics at the stand and landscape levels were developed to evaluate the impacts of increasing water levels and disturbance associated

with global climate change on mangrove forests of the Everglades. A hindcast simulation for 1886-1996 indicates that the periodicity and trajectories of a few major hurricanes accounted for most of the impact on forest structure of modern day mangrove forests across south Florida. As hurricane intensity increases over the next century, model projections suggest that future mangrove forests are likely to be diminished in average height and will contain a higher proportion of red mangroves. Sea-level rise will allow mangrove encroachment into freshwater marsh and swamp environments of the interior Everglades system that with minimal coastal erosion will increase mangrove expanse and reduce freshwater marsh coverage. South Florida human population estimates will continue to grow significantly and could indirectly affect freshwater flow and circulation that could exacerbate the rate and extent of sea-level rise. Mangrove systems of south Florida are already preserved in the public land trust of various U.S. government parks and refuges. Because they are fairly remote and insulated within large public land holdings, there

is little threat from human impact of coastal development, nor are there any feasible coping strategies for abating mangrove migration into upland habitats from sea-level rise.

## 12.1 Current Status and Stresses

Mangrove forests occupy intertidal settings of tropical and subtropical regions worldwide (Chapman, 1976; Duke, 1992). Their predominance along the land-sea interface makes these coastal forests vulnerable to sea-level rise, tropical storms, oil spills, and other disturbances, both natural and human-induced (Snedaker and de Slyva, 1987; Field, 1995; Hogarth, 1999; Boesch, et al., 2000). Because of their halophytic nature, mangroves tolerate the added stress of waterlogging and salinity conditions that prevail in low-lying coastal environments influenced by tides. Mangroves are highly productive ecosystems and provide valued habitat for fisheries and shorebirds (Gilmore and Snedaker, 1993). Global warming has been projected to increase sea water temperatures and expansion that may accelerate eustatic sea-level rise and further compound ecosystem stress in mangrove dominated systems (Gornitz, 1995; IPCC 1996).

Mangrove forests are prevalent along the coast of the Gulf of Mexico basin in the tropical latitudes of Texas and Florida and are limited geographically by lack of tolerance to freeze events (Odum et al., 1982). Scattered populations revegetate protected shores of the remaining northern gulf states in years between major freezes, mostly comprising the cold-hardy black mangrove, *Avicennia germinans* (McMillan, 1971; Sherrod and McMillan, 1985). Mangrove forests are universally composed of relatively few tree species and a single overstory strata (Lugo and Snedaker, 1972). Three species of true mangroves are common to intertidal zones of the Caribbean and Gulf of Mexico coasts, namely black mangrove, *Avicennia germinans* (L.) Stearn, white mangrove, *Laguncularia racemosa* (L.) Gaertn.f., and red mangrove, *Rhizophora mangle* L.

## 12.2 Coastal Margin of the Everglades Region, South Florida

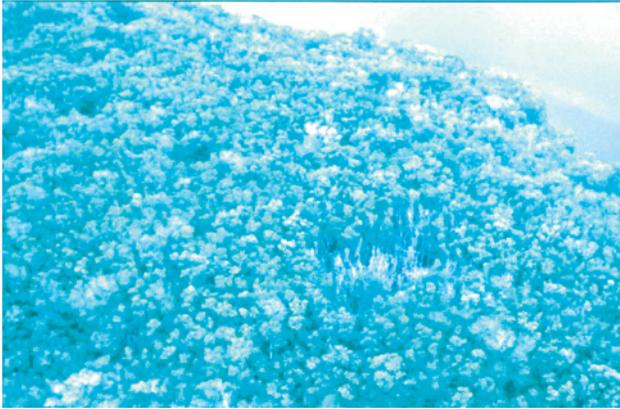
The larger extent of mangroves in the United States lies in south Florida in Lee (14,275 ha), Collier (29,126 ha), Monroe (94,810 ha), and Dade (33,931 ha) counties surrounding the Everglades (Odum et al., 1982). The near sea-level elevation and flat slope of the protected Everglades system accounts for one

of the largest contiguous tracts of mangrove forests found anywhere and punctuates their potential vulnerability to rising sea level and other climate changes. These forests are subject to coastal and inland processes of hydrology that are largely controlled by regional climate, disturbance regimes, and water management decisions. It is difficult to generalize the probable impacts of climate change given the myriad environmental settings where mangroves persist even within the Everglades.

Mangroves are adapted to tolerate coastal flooding and salinity (Lugo and Snedaker, 1972). Davis (1940) was among the first to describe the intertidal zonation and diverse geomorphic settings where mangroves colonize and persist in south Florida. While zonation has largely been attributed to salinity gradients, more recent field and experimental studies indicate that mangroves have wide tolerances to salinity and other soil factors (Hutchings and Saenger, 1987; Smith, 1992). Increases in relative sea level will eventually raise saturation and salinity conditions at ecotonal boundaries where mangroves are likely to advance or encroach upslope into freshwater marsh and swamp habitats. Other climate phenomena, such as hurricanes and lightning strikes, are frequent in south Florida and influence ecosystem health and recovery (Smith et al., 1994; Doyle et al., 1995). The impact of major hurricanes results in wide area forest damage of varying degrees from devastating blowdowns to intact, but defoliated canopies (Figure 1; Stoddart, 1963; Steinke and Ward, 1989; Roth, 1992; Wunderle et al, 1992; Doyle et al., 1995). Lightning strikes are frequent in this coastal region causing circular gaps of less than 0.1 ha wherein all trees within a given radius are killed by electrical conduction in saltwater (Figure 2; Smith et al., 1994). Other climate stresses can cause mangrove



**Figure 1.** Devastated mangrove forest in Everglades National Park in the aftermath of Hurricane Andrew in 1992.



**Figure 2.** Aerial view of mangrove forest canopy prior to Hurricane Andrew of a lightning gap with standing dead snags.



**Figure 3.** Mangrove impoundment at Ding Darling National Wildlife Refuge on Sanibel Island, Florida, where multiple rain storm events in as many decades have caused recurring stress and dieback of the local mangrove population.

dieback or decline including hard freezes (Lugo and Patterson-Zucca, 1977), severe drought and water deficits, as well as extreme precipitation events where water levels, if impounded, can rise acutely and cause massive dieoffs (Figure 3; Doyle, 1998). Rapid substrate collapse (subsidence) can occur following mangrove dieoff as a result of root zone decomposition that can be substantial enough to prohibit recolonization and spur coastal erosion (Wanless et al., 1994; Cahoon et al., 1998).

### 12.3 Hurricane Effects on South Florida Mangrove Communities

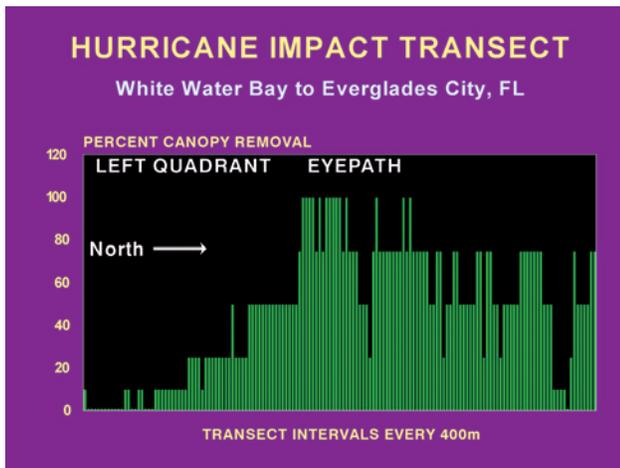
Mangrove ecosystems dominate the coastal areas of the lower Florida peninsula, where hurricanes frequently strike. Tropical storm frequency along any given stretch has been estimated at one event every 5-10 years. Climate change studies predict that tropical storm events may become more intense in a warming global environment (Emanuel, 1987). Numerous field studies have documented the susceptibility and vulnerability of neotropical mangrove species and systems to hurricane disturbance (Craighead and Gilbert, 1962; Stoddart, 1963; Craighead 1964, 1971; Roth, 1992, Wunderle et al., 1992; Smith et al., 1994).

More recent investigations by Doyle et al. (1994, 1995) of effects of Hurricane Andrew (1992) on south Florida mangroves relate how the physical and biological elements interact to explain the varying degrees of windthrow and mortality relative to hurricane intensity, path, and direction. Permanent field sites were established to assess the extent of forest damage and to monitor the rate and process of forest recovery following Hurricane Andrew (Figure 4). Canopy trees suffered the highest mortality particularly for sites within and immediately north of the storm's eyewall. The type and extent of site damage, windthrow, branch loss, and defoliation, generally decreased exponentially with increasing distance from the storm path. Right quadrant impacts were greater than left quadrant effects for the same given distance from storm center. Stand exposure, both horizontally and vertically, increased the propensity and probability of forest damage accounting for much of the local variability (Figure 5). Slight species differences were found where *Laguncularia race-*



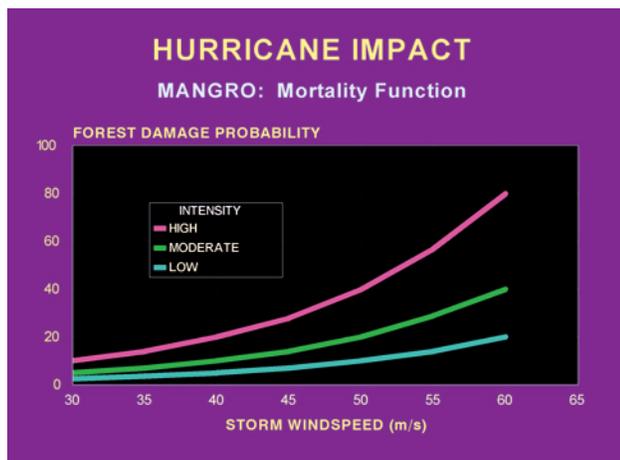
**Figure 4.** Map of mangrove extent and field plots in south Florida parks and refuges with overlay of storm track of Hurricane Andrew.

*mosa* exceeded *Avicennia germinans* and *Rhizophora mangle* in damage potential under similar wind conditions. Azimuths of downed trees were strongly



**Figure 5.** Damage profile of mangrove cover along a coastal transect of Everglades National Park perpendicular to the eyepath of Hurricane Andrew demonstrating the imprint of forward and backside impact (after Doyle et al., 1994).

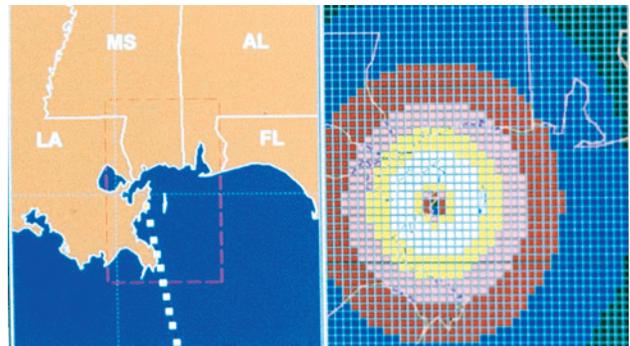
correlated with predicted windspeed and vectors based on a computer simulation of Hurricane Andrew. Lateral branch loss and leaf defoliation on sites without windthrow damage indicated a degree of crown thinning and light penetration equivalent to treefall gaps under normally intact forest conditions. Forest damage and tree mortality functions were constructed in relation to predicted windspeeds from these empirical data and incorporated into a mangrove forest simulation model for south Florida (Figure 6).



**Figure 6.** Forest damage probabilities and tree mortality functions constructed from field observations in relation to predicted hurricane windspeeds used for mangrove forest model application.

## 12.4 HURASIM Hurricane Model: Spatial Reconstructions of Hurricane History

A hurricane model, HURASIM, and a mangrove forest model, MANGRO, were combined in a spatially distributed landscape application to review the impact of hurricane history over the last century on forest structure of mangrove communities across south Florida (Doyle and Girod, 1997). A landscape modeling application was applied to test the importance of hurricanes in controlling mangrove forest structure and dynamics and to project the potential impact of increasing hurricane intensity of future storms under climate change (Doyle, 1998). HURASIM is a spatial simulation model of hurricane structure and circulation for reconstructing estimated windforce and vectors of past hurricanes (Doyle and Girod, 1997). The model uses historic tracking and meteorological data of dated North Atlantic tropical storms from 1886 to present and a graphics interface and for display (Figure 7). The model generated a matrix of storm characteristics (i.e., windspeed, direction, and distance) within discrete geographic units of the south Florida landscape that were then passed to the



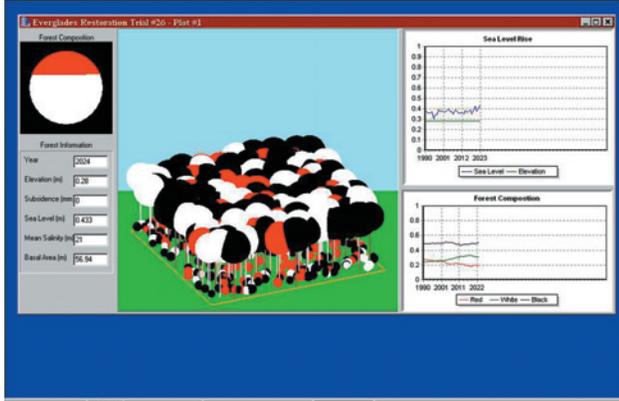
**Figure 7.** Sample graphics interface and spatial articulation of a reconstructed storm path of Hurricane Camille (1969) extracted from the HURASIM hurricane simulation model.

MANGRO model to predict forest response. This integrated, landscape-modeling approach offers the ability to evaluate the temporal and spatial variability of hurricane disturbance over the last century and in the future under climate at both the local and regional scale.

## 12.5 MANGRO Forest Model

MANGRO is a spatially explicit, stand-simulation model constructed for Neotropical mangrove forests composed of black mangrove, white mangrove, and red mangrove (Figure 8). MANGRO is an individual-

based model composed of a species-specific set of biological functions predicting the growth, establishment, and death of individual trees. MANGRO predicts the tree and gap replacement process of natural forest succession as influenced by stand structure and environmental conditions. The position of each tree is explicitly defined on a planar coordi-



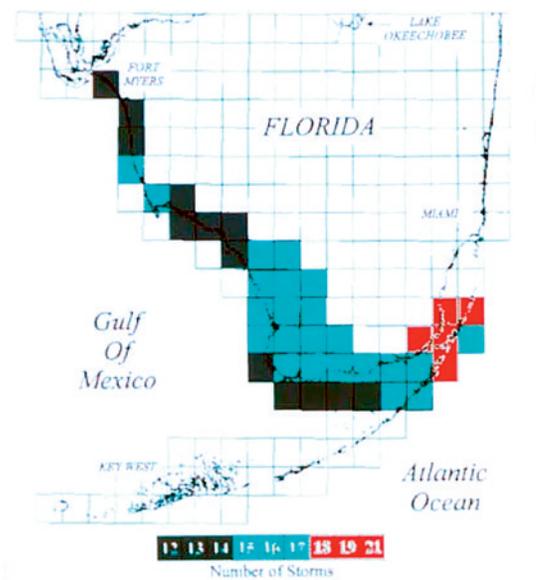
**Figure 8.** Sample graphics interface of the MANGRO model and a recruitment phase of mixed mangrove species composition.

nate system with a default stand area of 1 ha (100-m per side). Canopy structure is modeled as a three-dimensional process of crown height, width, and depth in relation to sun angle and shading by neighboring trees. Tree growth was based on growth potential for a given tree size reduced by the degree of light availability to the individual tree and species response to shade. Mortality was modeled as a stochastic process of age, suppression, and hurricane impact derived from damage probability curves developed from observed data of Hurricane Andrew (1992) impact (Doyle et al., 1994; 1995) (See Figure 6).

## 12.6 Hindcast Simulations of Hurricane Strikes and Mangrove Ecosystem Response

Both the MANGRO and HURASIM model simulations were projected onto a compartmentalized landscape of south Florida at a scale equal to a 7.5 minute quadrangle (Doyle and Girod, 1997, Doyle 1998). In total, 41 cells of an uneven matrix design were identified across the lower peninsula of Florida that contained distributions of mangrove habitat. Each cell represented an intact forest condition approximated by an independent simulation of the MANGRO model. Figure 9 shows a landscape template of mangrove distribution on a 10-km scale and the reconstructed frequency of hurricanes from 1886 to present across the south Florida peninsula produced

with the HURASIM model. The model demonstrates that hurricane incidence varies greatly over the range of mangrove distribution in south Florida. Four treatment effects were implemented including a no-hurricane simulation contrasted with a low, mod-



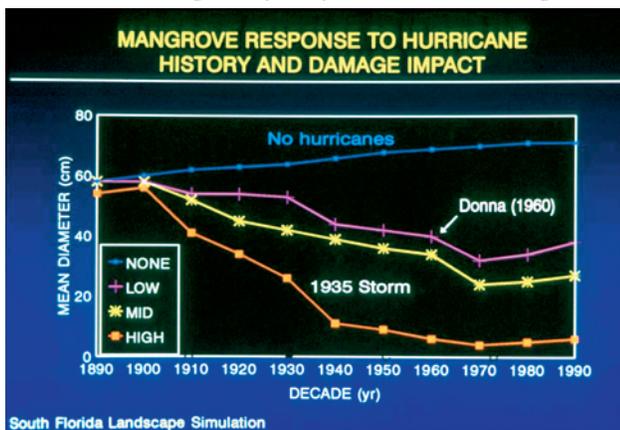
**Figure 9.** Landscape template of mangrove distribution on a 10-km scale and the reconstructed frequency of hurricanes from 1886 to 1996 across the south Florida peninsula produced with the HURASIM model (Doyle and Girod, 1997).

erate, and high mortality effect that increases with corresponding increases in windspeed (See Figure 6). A hindcast simulation for the period 1886 through 1989 was achieved by passing hurricane and site-specific information from the HURASIM model to the associated MANGRO simulation for common cells.

A cumulative assessment of hurricane impact was achieved by averaging stand attributes and size for the entire simulated landscape and hindcast interval (1890-1990). Simulations of hurricane tracks and history for south Florida showed that storm frequency and intensity varied across the landscape. Hurricane frequencies by quadrangle for the period of record showed that the number of storms with winds exceeding 30 m/s were more numerous on the Atlantic side than gulf side of Florida's lower peninsula (See Figure 9). The combined layering of hurricane impact showed that there are portions of the south Florida landscape that have received more frequent and more intense storm activity than other portions with either less frequent or less intense storm history. This finding indicates that different locations of the south Florida landscape have experienced a greater or lesser disturbance regime related to hurricane history. Hindcast simulations of actual

hurricane tracks and conditions seem to account for the structural composition of modern day mangrove forests across south Florida. The periodicity of major storms every 30 years in the 20th century may be the most important factor controlling mangrove ecosystem dynamics in south Florida. The most significant changes in forest structure followed major storms with tracks that subtended the larger distribution of mangrove habitat (See Figure 10). Global climate change models predict an increase in hurricane intensity over the next century that could further alter the structure and composition of this mangrove landscape. As damage potential increased from low to high, forest structure was increasingly reduced. Model results of climate change scenarios (high damage probability) indicate that future mangrove forests are likely to be diminished in stature and perhaps include a higher proportion of red mangroves (See Figure 10).

Present day forest structure from select locations across the south Florida landscape compared similarly to model results from the moderate storm damage function. The integrative modeling approach of combining physical models like HURASIM with biological models like MANGRO offers the ability to assess large scale and long-term processes of climate-related phenomena on our natural ecosystems. Decadal and longer time scale changes in hurricane behavior and regularity may be much more signifi-



**Figure 10.** Predicted changes in the composite structure of mangrove forest based on mean stand diameter for 1890-1990 for low, moderate, and high damage probability functions. Major storms are labeled and demonstrate the potential impact of single storms on landscape level.

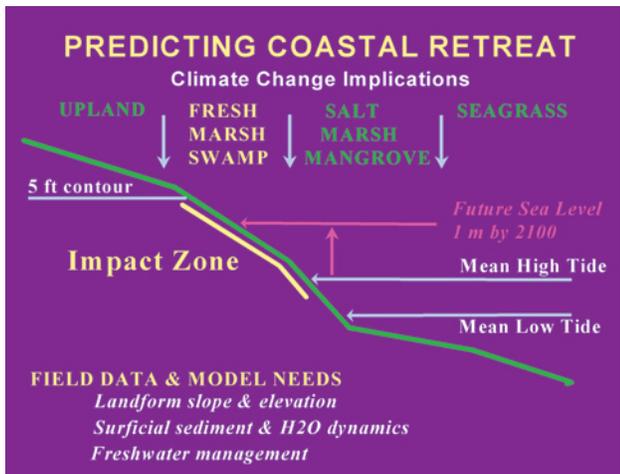
cant in shaping mangrove community structure and distribution on the landscape than can be evaluated by field studies alone.

## 12.7 Development of an Everglades Digital Elevation Model

Coastal forests of South Florida are subject to coastal and inland processes of hydrology largely controlled by regional climate, disturbance regimes, and water management decisions. The complex of climate change factors, namely sea-level rise, seasonal precipitation and temperature fluctuations, lightning storms, and hurricanes, will likely affect coastal margin habitats, including mangroves, to a greater degree than upland habitats of the Everglades. Modest changes in the climate cycle, particularly sea-level conditions, short- and long-term, can alter the hydrologic balance and tidal prism sufficient to alter habitat type and boundaries. Model applications were conducted to forecast mangrove migration under projected climate change scenarios of sea-level rise and saltwater intrusion for the Everglades coastal margin.

A high resolution model of surface topography was needed to predict the rate and fate of coastal inundation from sea-level rise over the next century. Tidal inundation and circulation are key factors controlling mangrove distribution in this coastal environment. The ability to predict landward transgression of mangroves caused by sea-level rise depends on the relationship between landward slope and elevation in relation to tide range and extent plus an understanding of relative sea-level rise (Figure 11). A historic topographic and drainage map produced by Davis (1943) with 1-ft contour intervals across the south Florida Everglades was rectified and digitized into a geographic information systems application. Boundary zones of major habitat classes were also digitized from the natural vegetation map of Florida produced by Davis (1943) to delineate the lower and upper elevations of the intertidal zone as defined by mangrove extent. The coastline was assigned an elevation of mean sea level while the upper transition zone of mangrove extent was approximated at mean high water for available tide datums along the southwest coast of Florida. These combined data sources and proxy contours served as baseline elevation values for constructing a digital elevation model (DEM) of south Florida.

A digital elevation model of the Everglades was developed to track the process and pattern of coastal inundation over space and time for various projections of sea-level rise. The TOPOGRID algorithm within the ARC-INFO geographic information system program was used to interpolate a high resolution,

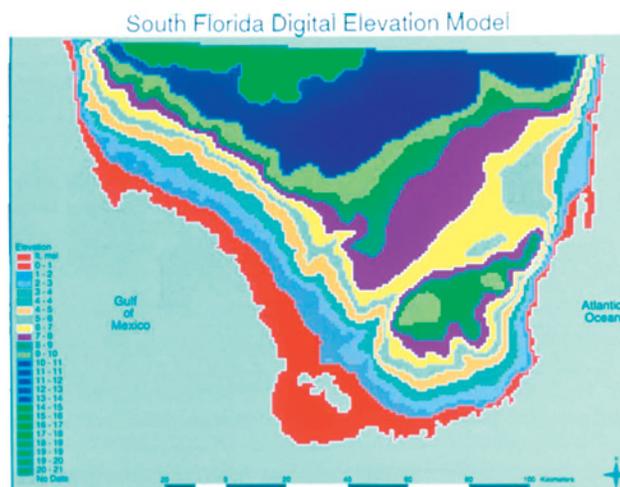


**Figure 11.** Concept diagram illustrating the relationship between landward slope and elevation in relation to the tidal prism and potential impact of sea-level rise.

100-m, DEM of the Everglades from the collective contour line graphs (Figure 12). The vegetation map layers were similarly classified into a raster-based image of habitat of the same scale to serve as base layers for the SELVA-MANGRO simulation model applications.

## 12.8 Forecasting Sea-Level Rise and Mangrove Migration across South Florida

The SELVA-MANGRO model represents a hierarchically integrated landscape model that manages the exchange of scalar information up, down, and across scale between linked simulation models SELVA and MANGRO (Doyle and Girod, 1997). SELVA is the Spa-



**Figure 12.** Digital elevation model (DEM) of south Florida based on spatial interpolation of elevation contour and proxy zonation heights taken from vegetation and topographic maps published by Davis (1943).

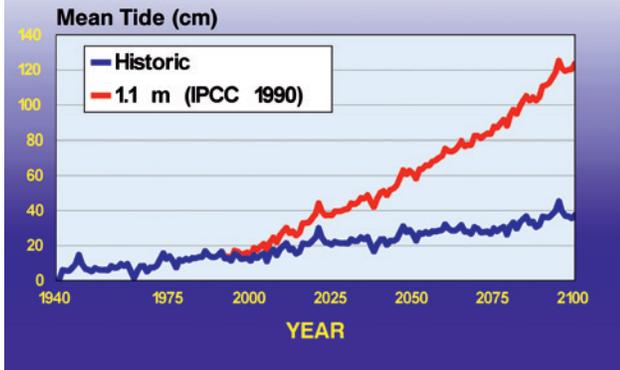
tially Explicit Landscape Vegetation Analysis model that tracks predicted changes in the biotic and abiotic conditions of each land unit (1 sq ha) on an annual basis for the entire simulated landscape. SELVA passes necessary information of environmental change to the MANGRO model at the stand level for each and all land units in the landscape profile. MANGRO returns a state condition of stand structure and composition to SELVA as predicted for each growth season or calendar year. Composite maps are produced that exhibit the predicted changes in species composition and forest migration, loss or gain, as influenced by changes in sea level.

Sea-level rise was modeled as a function of historic sea-level conditions at Key West, Florida, based on mean annual tide records (1940 to present) projected into the 21st century with the addition of curvilinear rates of eustatic sea level expected from climate change (Figure 13). The historic record was retained to mimic the natural cycle of high and low tidal variation attributed to astronomical and meteorological causes. The data record was extended into the next 100 years with the addition of multiple cases of eustatic rates of sea-level rise based on IPCC (1996) low, mid, and high projections obtained from global climate change models. Model simulations were achieved for each sea-level rise scenario by resetting the tidal prism for each case by calendar year.

The model is updated annually as to the predicted tide height which is then contrasted with the land elevation of each land unit to determine flood height or deficit. Flood height is then used to predict favored habitat condition and species regeneration based on probability functions of species and community tolerance to water level and salinity. Mangrove species establishment was modeled as a function of tidal sorting and presence or absence of parent trees in adjoining land units. Seeding probabilities favored red mangrove in persistently inundated soils, while black mangrove and white mangrove seedlings were favored in irregularly flooded soils. Mangrove regeneration and migration were allowed in any land unit where tidal inundation exceeded soil elevation for any given year. In years where flood height exceeds tolerance for the prevailing habitat condition and favors a different habitat type, the model updates the habitat array to reflect a change in ecological succession. Model output consists of land unit counts and hectares of converted habitat, loss and/or gain, by calendar year.

## Sea-Level Rise Projections

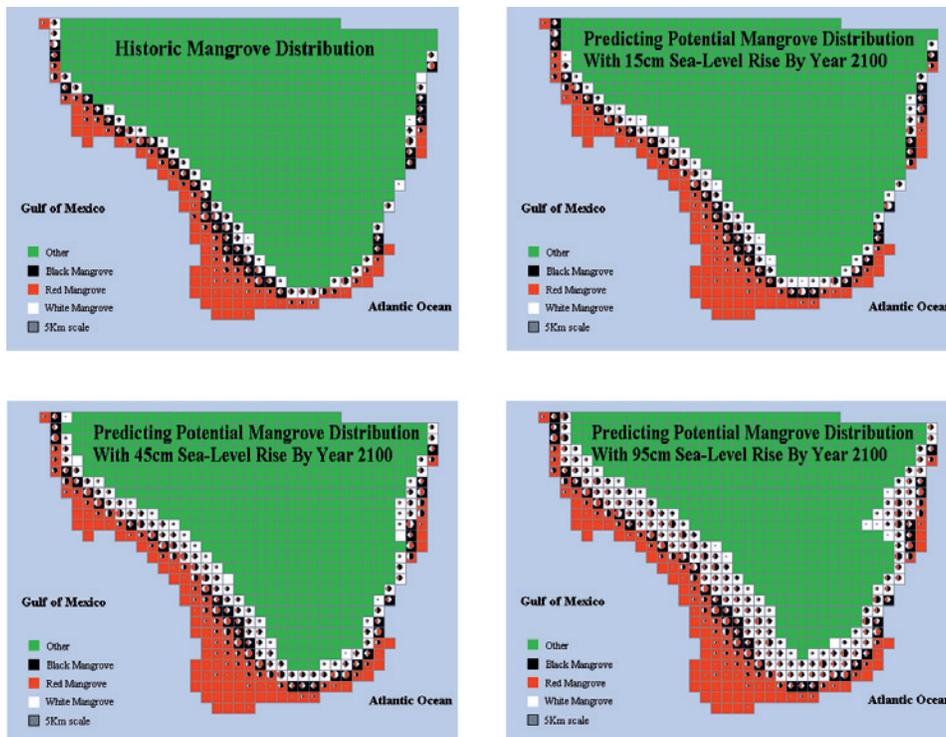
Tide Record, Key West, Florida



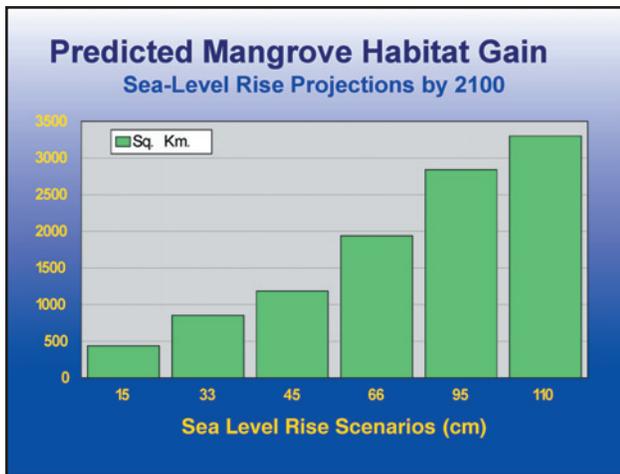
**Figure 13.** Sea-level rise functions of historic sea-level conditions at Key West, Florida based on mean annual tide records (1940 to present) projected to year 2100. Projected eustatic sea level rates were from climate change of up to 1.1-m were constructed for model applications.

Model results show that species and forest cover changed over space and time with increasing tidal inundation across the simulated landscape for all sea-level rise scenarios. Figure 14 contrasts the degree of mangrove migration compared with contemporary distribution and selected sea-level scenarios, low,

moderate, and high, expected by 2100. The greater the rate of sea-level rise the faster or more extensive the encroachment of mangroves onto the Everglades slope. The model shows that freshwater marsh and swamp habitats will be displaced as the tidal prism increases over time as it moves upslope. Under these modeling assumptions, mangrove habitat will increase over the next century under climate change and conversely, freshwater marsh/swamp is expected to decrease. Figure 15 shows the predicted land area that mangroves will gain at the expense of other freshwater habitats over the next century relative to a host of predicted estimates of climate change-induced sea-level rise. Coastal erosion is a realistic probability driven more from hurricane influence than just sea-level rise alone. In spite of major storm strikes along the southwest coast where some tidal flats once dominated by mangroves remain unvegetated due to hurricane impact, the coastline over the last 60 years has remained remarkably stable. The land building qualities of mangroves to capture and hold marine sediment deposition is sufficient to buffer normal wave energy of the Gulf of Mexico in the absence of severe tropical storms.



**Figure 14.** Contemporary and predicted distributions and species composition from inland mangrove migration under selected IPCC (1996) sea-level scenarios, low (15 cm), moderate (45 cm), and high (95 cm), expected by 2100.



**Figure 15.** Predicted land area that mangroves will gain at the expense of other freshwater habitats over the next century relative for various projected estimates of climate change induced sea level rise.

## 12.9 Socioeconomic Implications

Projected human population growth of south Florida is among the highest rates nationally. Coastal counties, Collier, Lee, and Monroe, along the southwest “Gold” coast of Florida neighboring the northern Everglades, are projected to grow at 83%, 62%, and 28%, respectively by year 2025. The burgeoning growth of south Florida places a high demand on public resources, such as electricity, water, and land. The competing needs for freshwater may be the first and most critical resource that will likely impinge on surrounding conservation areas and coastal preserves. Changes in freshwater storage and flow, above and below surface, will indirectly, if not directly, speed the effect and extent of sea-level rise without mitigating strategies. The Greater Everglades Ecosystem Restoration Program has been funded by Congress to insure that natural systems will be enhanced with more responsible freshwater controls. Public demand for potable water supplies must be met by other means such as desalinization plants and other conservation measures.

Study findings show that projected sea-level rise of any rate will result in further inland penetration of saltwater that will effectively prompt mangrove migration into upslope marsh and swamp habitats across the coastal margin of the Everglades. Because of the protected status and isolation of the larger Everglades system, sea-level rise will likely increase mangrove distribution and reduce the proportion of some freshwater habitats with little or no socioeconomic impact depending on any changes in freshwater management. Model predictions for all

sea-level rise cases indicate significant gains in coastal mangrove habitat that could actually enhance local fisheries, but could also compromise other wildlife benefits. The local economy is mostly dependent on tourism and recreation which will be unaffected by these climate change impacts.

The U.S. Government holds in public trust the entire land area encompassing the coastal margin of the Everglades. There are no private or commercial interests that will suffer directly from the probable shift in habitat proportions from freshwater dominated systems to coastally dominated habitats. While the model predicts no actual land acreage losses, it is possible that the interaction of sea-level rise and hurricanes may promote more coastal scouring than is predicted. The projected losses of freshwater habitat could negatively impact wildlife resources more dependent on freshwater wetlands than mangroves. It is not known whether existing animal populations can compensate for these habitat losses with more intensive habitat utilization.

## 12.10 Coping Strategies

Coping strategies are likely not warranted given the minimal losses to the local economy and the limited options to remediate the natural process of coastal transgression. Freshwater control structures and long-term management strategies are in place to restore and revitalize historic flow and habitat conditions. The use of freshwater head may be sufficient to slow or retard mangrove migration where and when warranted.

## 12.11 Adaptation and Future Research

Freshwater conservation measures must be implemented to accommodate the current population boom in south Florida counties to prevent any problems of water utilization and wastewater disposal on surrounding ecosystem health. Coastal developments in the region are highly regulated though inland developments that alter watershed relations and recharge could be of greater concern. As a state, Florida has advanced environmental regulation for coastal development and mangrove protection that is sufficient to preserve their coastal resources. The absence of any inholdings or other private or commercial investments in the Everglades presents no significant impediments to coastal wetland migration to warrant consideration. Coastal adaptation strategies are neither warranted nor cost effective

considering what control could already be in place to moderate freshwater flow through the Everglades as an alternative to sea-side engineering projects. Given the legacy and high profile of the Everglades and recent government funding for water management control and ecosystem restoration, it should be recommended that long term monitoring of existing conditions should be implemented to document real-time events that affect mangrove/marsh migration or decline. Monitoring efforts would also be useful to calibrate and validate model applications such as described herein to refine current predictions.

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