Chapter 6: Modeling Global Change Effects on Coastal Forests

by

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Abstract: Predictions about global climate change include increases in the intensity of tropical storms, to which the low-lying Gulf of Mexico and South Atlantic coasts are particularly vulnerable. The direct damage from wind and surge force associated with tropical hurricanes can be sufficient to alter coastal forest structure and diversity. Landscape simulation models were developed to evaluate the impacts of increasing water levels and disturbance associated with global climate change on mangrove forests of the Everglades, Florida. A hindcast simulation for 1886–1989 indicates that the periodicity and trajectories of a few major hurricanes accounted for most of the impact on the 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. In the Big Bend area of northwest Florida, land elevation and water depth are key factors controlling habitat type. A digital elevation model of the area was constructed to track the process and pattern of coastal inundation over space and time for the low, mid, and high sea-level rise projections of the Intergovernmental Panel on Climate Change. The three sea-level scenarios indicated that major portions of this coastal zone will be permanently inundated over the next century, bringing about a combined migration and loss of some habitats. Results show that there is a large land base that will be quickly converted from coastal saltwater and freshwater marsh to open water and from coastal pine forest to emergent marsh, on a scale approaching the land loss that has been experienced in south Louisiana, 65–90 km^2 per year.

Introduction

In this chapter I present a summary of an investigation into the effects of Hurricane Andrew on mangrove forests in southwest Florida and how the results of the study were used to develop computer simulation models that demonstrate the impacts of the expected increases in water levels and disturbance associated with global climate change.

The southeastern coastal region is composed of vast areas of wetland habitat for wildlife and other economically important coastal resources such as shellfish. Located on the interface between sea and land, these wetland habitats are especially vulnerable to sea-level rise and to drought and flooding aggravated by large-scale climatic shifts (Giorgi et al. 1994; Intergovernmental Panel on Climate Change 1995b). Coastal wetlands along the South Atlantic and Gulf of Mexico coasts are especially sensitive because these ecosystems exist in a dynamic equilibrium between subsidence and accretion. This equilibrium is already being threatened by sea-level rise (Stevenson et al. 1986). In some coastal areas, accretion is insufficient to balance sea-level rise, resulting in increased flooding, saltwater intrusion into freshwater wetlands, and mechanical erosion (Stevenson et al. 1986).

Dramatic losses of the emergent marsh and forested wetlands of coastal Louisiana in recent decades may serve as a precursor of climate change impacts, though other human-induced causes also may be at fault. Increased tropical storm activity may also accompany global warming as a function of higher sea temperatures: the kinetic energy of tropical storms and hurricanes is fueled from the heat exchange in warm tropical waters, and therefore an increase in seawater temperature can be expected to increase the probability of greater storm intensities (Emanuel 1987). Any increase in storm intensity will impose direct and indirect loss of wetland function.

The goal of this study was to develop a suite of spatial simulation models to predict the impacts of global climate change on the coastal wetlands of the Gulf Coast region. Computer simulation models can help benefit field and laboratory studies by providing a comprehensive means of integrating knowledge of natural systems into a holistic framework. Their greatest use is demonstrated in addressing problems that are spatially and temporally extensive and dynamic, such as global climate change. Simulation models can be particularly useful in evaluating variable or long-term environmental impacts that otherwise cannot be tested reliably with experimental methods. The same holds true for spatial models designed to account for multiscale processes and phenomena that interact to control ecosystem structure and function. Applications of this study included the coastal habitats of St. Marks National Wildlife Refuge, Florida, and mangrove-marsh of Everglades National Park, Florida, and adjoining Federal lands. Field studies were conducted to fill in knowledge gaps regarding species and community response to fire and hurricanes. Spatial simulation models were applied to predict habitat loss and change under given sea-level rise projections and hurricane disturbance regimes.

Mangroves

Mangrove ecosystems are at their most northern limit along the South Atlantic coastline of Florida and in isolated refugia of the gulf coast of Louisiana and Texas. These are marine-based forests which are specially adapted to colonize and to persist in saline intertidal waters. Three species are common to the United States, black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), and red mangrove (*Rhizophora mangle*). Black mangrove is the most cold tolerant of the three species, though its susceptibility to frost and freeze damage prevents it from reaching full maturity in the northern extent of its range. Mangroves, which are highly productive ecosystems and provide valued habitat for fisheries and shorebirds, are susceptible to lightning and hurricane disturbance, both of which occur with great frequency in south Florida. The degree to which mangroves can tolerate prolonged flooding and extreme saline conditions is not known, though evidence suggests that high water episodes from above-normal rainfall may be responsible for recent die-offs. Sea-level rise from climate change will undoubtedly allow mangroves to encroach inland depending on the resiliency of emergent wetland types and assuming that the prevailing vegetation can keep pace with the rate of coastal inundation.

Experimental and Field Studies Supplement Modeling Applications

Field and experimental studies were conducted as part of this study to improve our understanding of mangrove species tolerance and community zonation and to aid modeling trials for study sites in north and south Florida. Permanent plots and greenhouse experiments were instituted to determine the growth habits and ecology of mangrove species following hurricane disturbance. Field sites also were established along the northern gulf coast to calibrate the impact of fire and hurricanes on the growth and succession of pine flatwood/marsh systems.

Hurricane Effects on South Florida Mangrove Communities

Mangrove ecosystems predominate the coastal areas about the lower Florida peninsula where hurricanes are common. Tropical storm frequency along any given stretch has been estimated at one major event every 5–10 years. 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 Hurricane Andrew in 1992 on south Florida mangroves explained the varying degrees of windthrow and mortality relative to hurricane intensity, path, and direction. Global climate change forecasts suggest that these coastal forests will be among the ecosystems most immediately threatened by projected increases in sea level, salinity, 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. For my study, a hurricane model, HURASIM, and a mangrove forest model, MANGRO, were combined in a spatially distributed landscape application to review the impact of hurricanes over the last century on forest structure of mangrove communities across south Florida. This integrated landscape modeling approach offered the ability to evaluate the temporal and spatial variability of hurricane disturbance over the last century and on the local and regional scale.

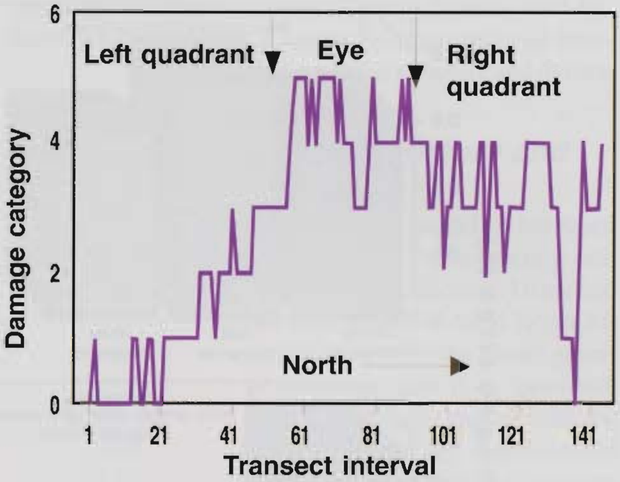


Figure 6-1. Mangrove forest damage assessment of coastal transect based on visual interpretation of canopy damage category across hurricane impacted zone of Everglades National Park and Ten Thousand Islands National Wildlife Refuge of south Florida.

Population Studies

Forest inventories were conducted before and after the passage of Hurricane Andrew in 1992 to assess and monitor the effects of hurricanes and climate change on mangrove forests. Remote videography was taken at low altitude by helicopter over mangrove forests along the southwestern coast of Florida to derive a coastwide assessment of damage extent and pattern. Coastal and inland transects which were perpendicular to the hurricane path were flown within the forest boundary of mangrove extent over Ten Thousand Islands National Wildlife Refuge and Everglades National Park. Continuous video footage was taken along these transects with recorded voice transmissions of coordinate location, altitude, flight speed, bearing, and other pertinent observations of ground damage on the tape. A separate global positioning system (GPS) unit tracked exact helicopter movement along with the video. Video analysis involved both visual and image analysis protocols to assess the degree of damage, windfall orientation, and canopy height of the forest below. A systematic sampling approach was employed to preselect video frames for analysis and georeferencing.

The degree of forest damage increases within the eyepath of storms with a skewed distribution of damage that is lesser on the backside of storms compared to the forwardside for the same distance from storm center (Fig. 6-1). The results of this study demonstrate the utility of videography in capturing time- and space-dependent responses (i.e., site impact and recovery) and in increasing the overall scale and area of assessment for large phenomena such as hurricanes. Similarities and differences between the inland and coastal transects showed the general pattern of the eyetrack where winds were highest and the circulation pattern of hurricane winds. Aerial videography proved to be an efficient and timely means to document large-scale hurricane damage and may likewise help to monitor ecosystem recovery in the coming years.

Additional field studies were also conducted to obtain mangrove growth and stand structure data for model development. Over 20 fixed plots have been established in Everglades National Park and adjoining USFWS refuges and state lands. Over 2,000 mangrove trees have been stem-mapped and measured. Field assessments of damage to mangrove forests from Hurricane Andrew have been analyzed and published (Doyle et al. 1995). Permanent field sites were established to assess the extent of forest damage and to monitor the rate and process of forest recovery after Hurricane Andrew moved across the lower Florida peninsula. It was found that 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, and accounted for much of the local variability. Slight species differences were found where white mangrove exceeded black mangrove and red mangrove in damage potential under similar wind conditions (Fig. 6-2). Azimuths of downed trees were strongly correlated with predicted

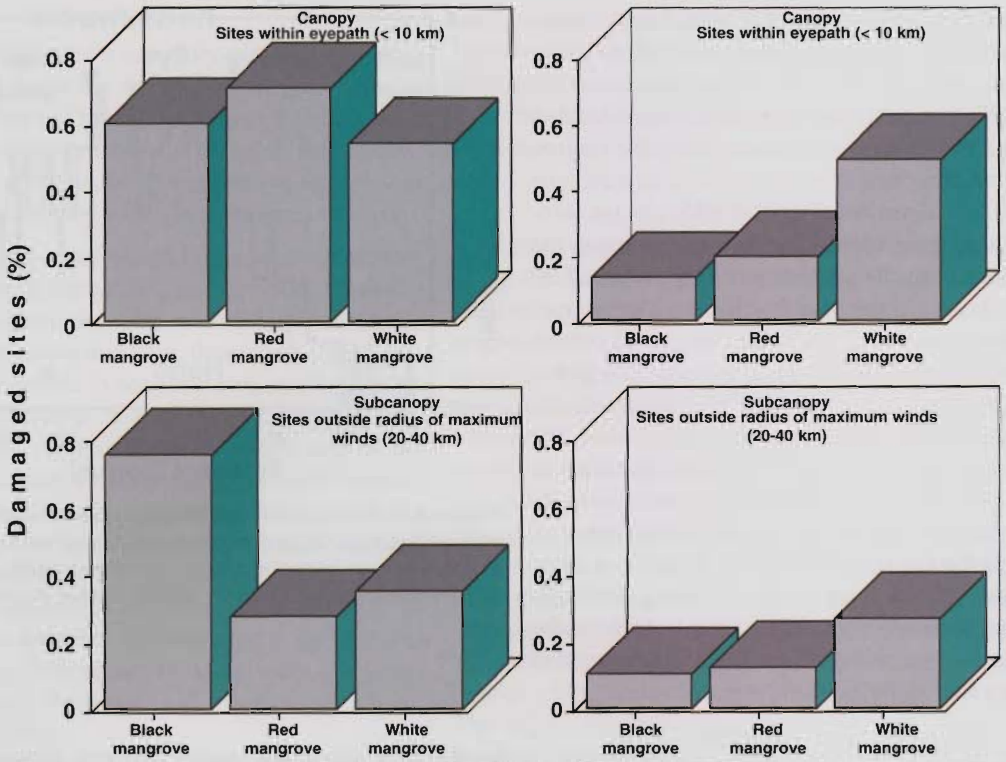


Figure 6-2. Proportion of severely damaged stems by species and crown class for sites within the eyepath and outside the radius of maximum winds.

windspeed and vectors based on a simulation of Hurricane Andrew (Fig. 6-3). Lateral branch loss and leaf defoliation on sites without windthrow damage indicated a degree of crown thinning and light penetration equal to treefall gaps under normally intact forest conditions. Measurements of photosynthetically active radiation (PAR) attenuation through mangrove canopies differentially impacted by hurricane winds of estimated force offer a means to calibrate actual wind damage probabilities on mangrove forests (Fig. 6-4).

Little has been documented about the adventitious sprouting habits of mangrove species and how mangrove communities regenerate following disturbance. Hurricane Andrew ravaged the mangrove communities of south Florida and left extensive tracts of downed trees. A field study was conducted in the Ten Thousand Island region of the northern Everglades to determine the process and rate of mangrove regeneration in blowdown sites. Seedlings and stem sprouts of black, white, and red mangroves were measured for diameter, height, and node development from two sites of comparable species and structural composition. Nodes were counted, and the length and diameter of internodes were recorded. Sampled trees included stump and bole sprouts of downed and damaged black mangrove and white mangrove which coppiced prolifically in contrast to red mangrove. Stump sprouts were on

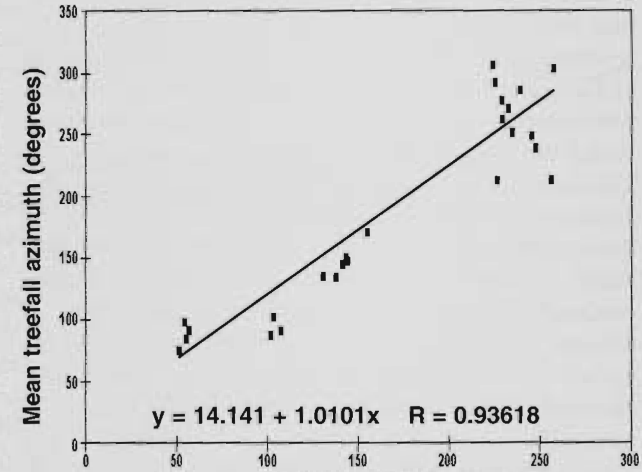


Figure 6-3. Scatter diagram and regression of actual mean treefall azimuths by site and predicted wind angle at peak hurricane wind speeds from the HURASIM simulation for all sample sites.

average more than twice the shoot size, height, and diameter compared with surrounding bole sprouts and seedlings. Patterns of node development demonstrated synchronous elongation within species and differences in node counts between species. Site, storm, and stem conditions

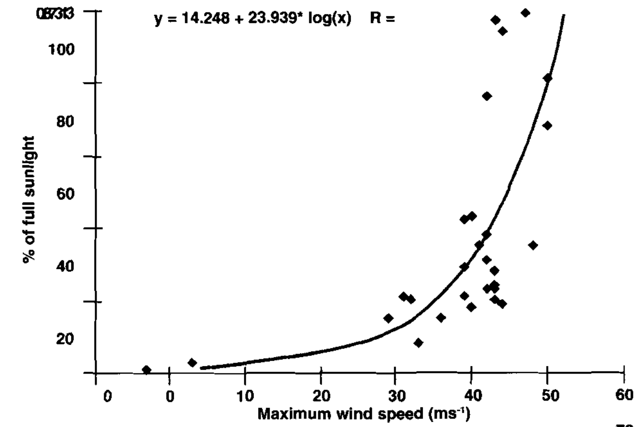


Figure 6-4. Scatter diagram and curvilinear fit of percent light (PAR) penetrating the residual forest canopy and maximum predicted wind speed from the HURASIM simulation for all sample sites.

may account for varying degrees of coppice success and seedling responses. The findings suggest that different rates of forest recovery might be expected depending on the prevalence of stump sprouting.

Modeling Climate Change Applications for the Gulf Coast Region

Wetland systems are likely to experience dramatic changes as a consequence of elevated carbon dioxide and associated environmental effects of climate change. Every level of biotic organization from the individual to the biome has a unique set of scalar and temporal properties and processes that ultimately influence structure and composition. It is this complex mix of controlling factors operating at different space and time scales that confounds efforts to identify unifying concepts and methods for classifying and analyzing natural systems. Experimental studies are limited by design to addressing questions at a single space or time scale. Simulation models, on the other hand, offer the potential to integrate across spatial and temporal scales. Elucidating the impact of climate change on wetland systems requires both the explicit consideration of the many spatial and temporal scales at which system responses occur and also the incorporation of those links and feedbacks between these scales as can be expressed with the development of computer simulation models.

For this study, a hurricane simulation model, HURASIM, was developed and applied to correlate estimated wind speeds and vectors of past hurricanes with field data (Doyle and Girod 1997). Model output was also used as input to a landscape simulation of south Florida mangroves. MANGRO, a mangrove community dynamics model, has been developed to simulate the birth, growth, and death of mangrove tree species on a square hectare forest plot. A landscape simulation model of south Florida (SELVA-MANGRO) was applied to test the importance of hurricanes in controlling mangrove forest structure and dynamics (Doyle and Girod 1997).

Simulating Hurricane History and Impact

HURASIM is a spatial simulation model of hurricane structure and circulation intended for reconstructing estimated windforce and vectors of past hurricanes. Using historic tracking and meteorological data of dated North Atlantic tropical storms from 1886 to 1990, the model generates a matrix of storm characteristics (i.e., quadrant, windspeed, and direction) within discrete spatial units and time intervals specified by the user for any specific storm or set of storms. HURASIM recreates the spatial structure of past hurricanes based on a tangential wind function, inflow angle offset, forward speed, and radius of maximum winds. Data input for the model includes tracking information of storm position, latitude and longitude, and maximum sustained wind speed every six hours or less. The model offers a suite of mathematical functions and parameter sets for the tangential wind profile taken from other hurricane studies (Harris 1963; Bretschneiger and Tamaye 1976; Neumann 1987; Kjerfve et al. 1986; Boose et al. 1994). The radius of maximum winds is determined from the reported maximum sustained wind input and a set of empirical equations. HURASIM model output from Hurricane Andrew was correlated with field data to construct data tables of damage probabilities by site and species and to determine critical windspeeds and vectors of tree mortality and injury. HURASIM has also been applied to reconstruct probable windfields of past hurricanes for remote field locations and correlated with tree ring growth patterns and direction of leaning trees and downed logs (Doyle and Gorham 1996). HURASIM has also been used to construct landscape templates of past hurricane activity that are linked with landscape simulation models of coastal habitat.

MANGRO Forest Model

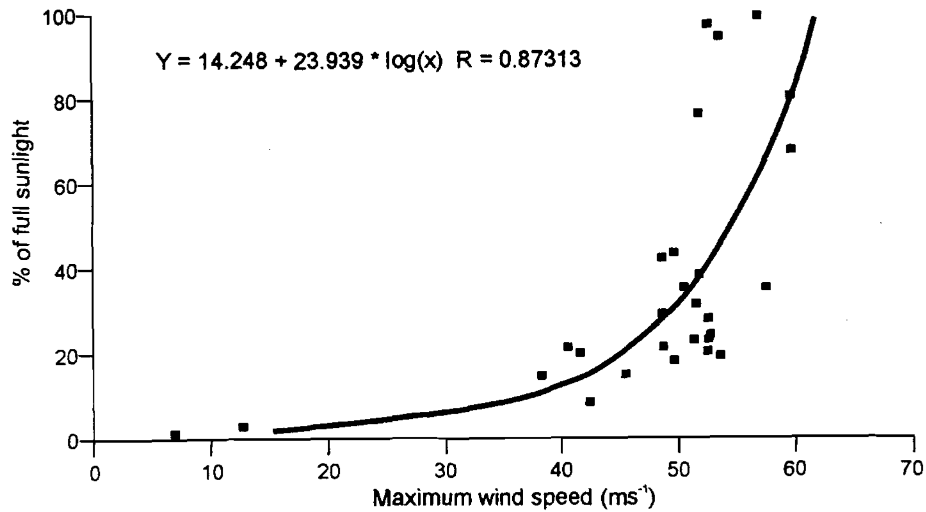
MANGRO is a spatially explicit stand simulation model constructed for Neotropical mangrove forests composed of black mangrove, white mangrove, and red mangrove. This individual-based model is composed of a species-specific set of biological functions predicting the growth, establishment, and death of 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 coordinate system with a default stand area of 1 ha (100 m per side). Stand configuration was based on intact forest conditions with no edge effects. Canopy structure is modeled as a three-dimensional process of crown height, width, and depth in relation to

Errata sheet

Citation:

Guntenspergen, G.R., and B.A. Vairin, editors. 1998. Vulnerability of coastal wetlands in the Southeastern United States: climate change research results, 1992-97. U.S. Geological Survey, Biological Resources Division Biological Science Report USGS/BRD/BSR–1998-0002. 101 pp.

Figure 6-4 on page 71 should appear as follows:



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 available to the individual tree and species response to shade. Mortality is modeled as a self-thinning process dictated by prolonged suppression, senescence, and disturbance factors, primarily hurricanes.

Hierarchial Integration of MANGROVE and HURASIM for South Florida Landscape

Both MANGRO and HURASIM were projected onto a compartmentalized landscape of south Florida at a scale equal to a 7.5 minute quadrangle. Forty-one cells of an uneven matrix design were identified across the lower peninsula of Florida, which contains mangrove habitat. Each cell represented an intact forest condition approximated by an independent simulation of the MANGRO model. Initial forest conditions were set with a normally distributed population of mature mangrove trees approximating a mean stand diameter of 50 cm and a mean stand age of 125 years. Seedling ingrowth was maintained stochastically at 1 plant per square meter every year to maintain a fully stocked stand for continuous recruitment. Equal probability was given to seedling recruitment by any species for any land area. Tree growth was constrained by size and light availability. A logistic growth function was constructed with observed data and generalized for all species taken from Craighead (1971) and Doyle et al. (1995). Stand data from 10-, 30-, and 60-year-old stands were used to approximate an empirical growth curve (Doyle and Girod 1997). Light availability was calculated for the crown zone and height of each tree as a function of light penetration through the canopies of taller neighbors. Light attenuation was calculated with Beer's Law based on a maximum leaf area index of 5.5. Growth was limited by shade tolerance (red mangrove having more shade tolerance than black mangrove, which in turn has more than white mangrove) based on a set of light response curves constructed from a concurrent experimental study (Doyle and Girod 1997). Sea-level and salinity conditions were assumed to be optimum for this simulation for all quadrangles whether seaward or not. Mortality was modeled as a stochastic process of age, suppression, and hurricane impact derived from damage probability curves developed from observed data of the effects of Hurricane Andrew in 1992 (Doyle et al. 1994, 1995) (Fig. 6-5). If in any given year of the simulation a predicted hurricane windforce exceeded 30 m/s, a probability was derived based on windspeed from which a percentage of the standing crop or trees were stochastically removed from the forest simulation. Trees that failed to maintain 30% of potential growth accumulated an increasing probability of death by suppression such that less than 1% were likely to survive 10 years.

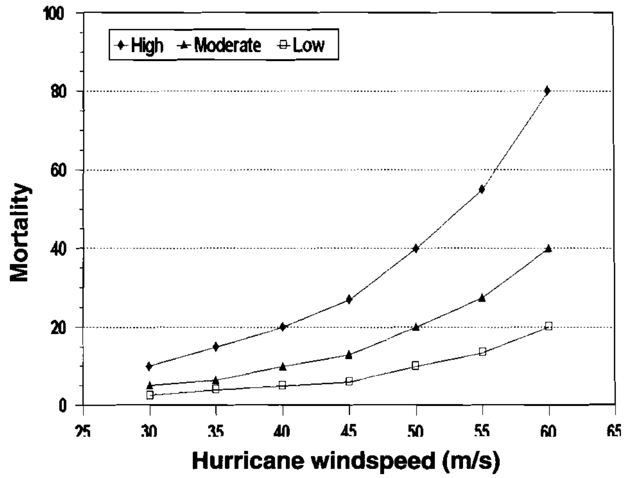


Figure 6-5. Damage probability curves calibrated from field observations showing the percentage of mangrove trees killed at given predicted wind speeds under expected hurricane impact (moderate) and for extreme (high) and nominal (low) impact scenarios.

Hindcast Simulations of Hurricane Tracks and Mangrove Community Response

Four treatment effects were implemented in this study, including a no-hurricane simulation contrasted with a low, moderate, and high mortality effect that increases with corresponding increases in windspeed (Fig. 6-5). A hindcast simulation for 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 time interval from 1890 to 1989. Simulations of hurricane tracks and history for south Florida showed that storm frequency and intensity varied across the landscape (Doyle and Girod 1997). 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 the gulf side of Florida's lower peninsula (Fig. 6-6). The southwest coast of Florida has endured stronger storms on record than the gulf and Atlantic coasts to the north. 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.

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 this century may be the most important factor controlling mangrove

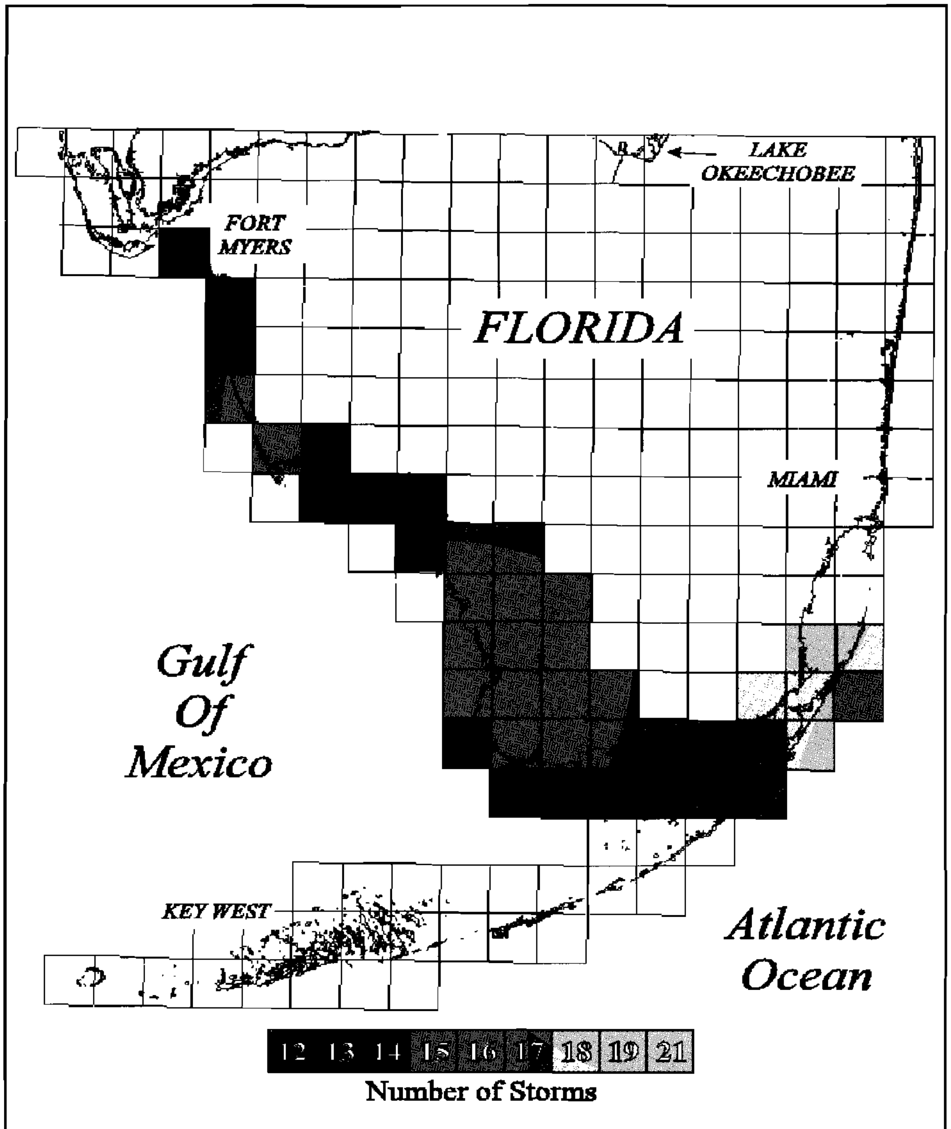


Figure 6-6. Frequency of hurricane strikes of Category 2 storms or greater (> 30 m/s) by quadrangle across south Florida predicted by HURASIM model for mangrove habitat for the period 1886-1989.

ecosystem dynamics in south Florida. The most significant changes in forest structure summarized by decade followed a few major storms with tracks that subtended the larger distribution of mangrove habitat (Fig. 6-7). Global climate change models predict an increase in hurricane intensity over the next century that may further alter the structure and composition of this mangrove landscape (Emanuel 1987). As damage potential increases from low to high, forest structure is 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. 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 natural ecosystems. Decadal and longer time scale changes in hurricane behavior and regularity may be much more significant in shaping mangrove community structure and distribution on the landscape than can be evaluated by field studies alone.

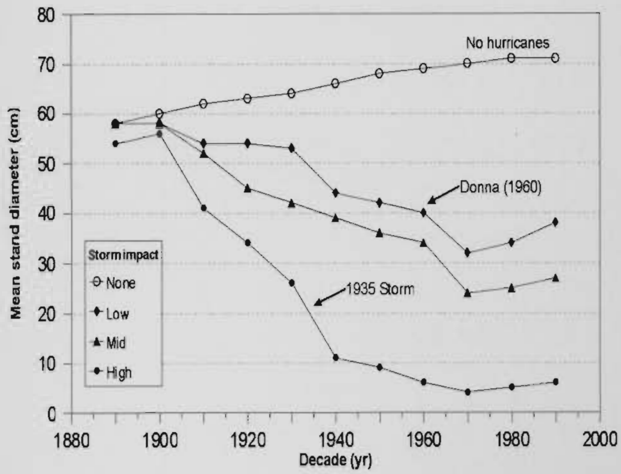


Figure 6-7. Mean stand diameter (cm) for a composite sampling of all 41 stand simulations of mangrove habitat for each decade under no-hurricane, low, moderate, and high impact scenarios for the period of hurricane history 1886-1989.

Projecting Land Cover Change and Shift of Marshes and Forests in Northwest Florida

Wildlife preserves and refuges in coastal areas of our nation are slowly being inundated by increasing sea level. Warming of our global environment threatens to speed the rate of sea-level rise and perhaps further amplify the detrimental effects of tropical storms, droughts, and lightning fires. During this study, research was conducted to examine the impacts of possible climate change scenarios on the functional wetland landbase and habitat of Federal parks and refuges along the Gulf of Mexico. A site application of a GIS-based simulation model, WETLANDS, was developed to predict ecosystem response to changing environmental conditions for wetland complexes of the Big Bend region in northwest Florida. The model contains functional attributes of community sensitivity to hydrologic conditions linked with a GIS data base of site characteristics, including habitat type, elevation, soils and land use.

Regional Study Site, Big Bend, Florida

The site application includes both the aquatic and terrestrial habitats of St. Marks National Wildlife Refuge in the Big Bend region of northwest Florida (Fig. 6-8). The refuge is situated approximately 32 km south of Tallahassee and covers parts of Wakulla, Jefferson, and Taylor counties. The total area of federally owned land incorporates 26,163 ha. Of the total area, 12,758 ha are open water in

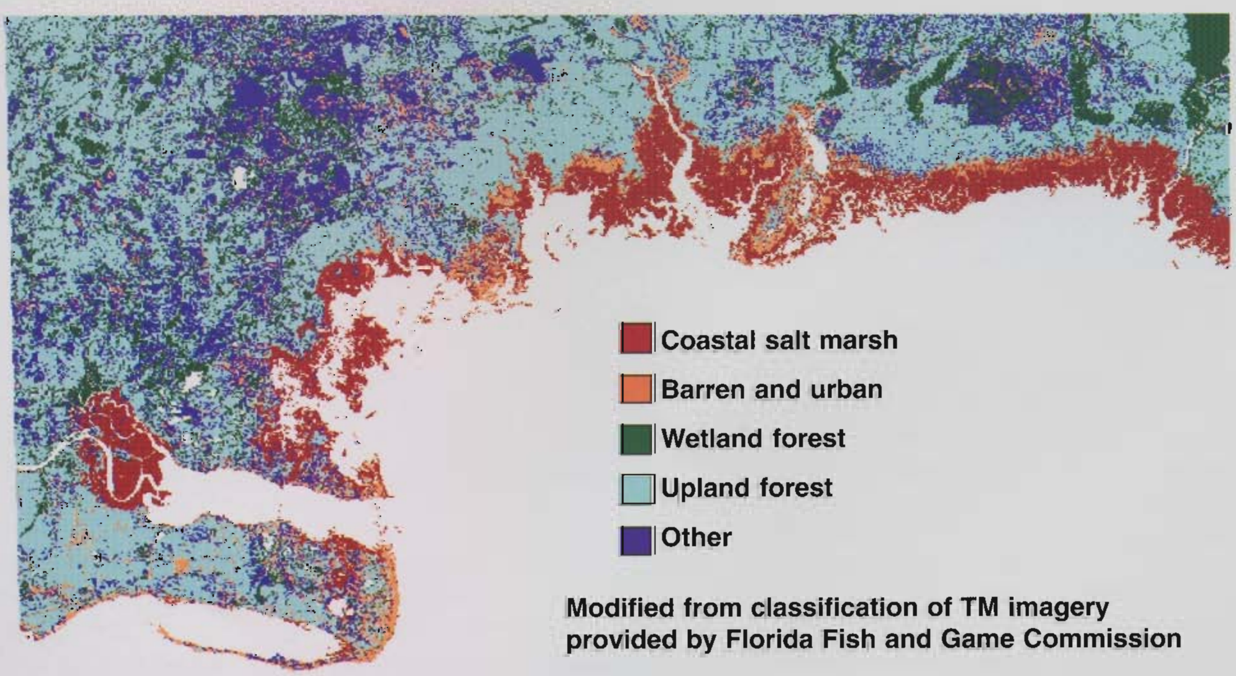


Figure 6-8. Habitat map of Big Bend coastal region including the area of St. Marks National Wildlife Refuge south of Tallahassee, Florida.

Apalachee Bay and 12,993 ha are forest and marsh. The refuge is bordered by Apalachee Bay on the south, Ochlockonee Bay on the west, and Aucilla River on the east. The reserve was purchased in 1929 and is one of the oldest refuges in the entire system of the U.S. Fish and Wildlife Service. The refuge landscape is characterized by a relatively low elevational gradient that is intersected by several rivers and a number of freshwater springs and intertidal creeks. Upland pine sandhills drain into wet pine flatwoods and hardwood swamps within the freshwater zone and into tidal salt marsh and mudflats at bay's edge. Seagrass beds are abundant throughout Apalachee Bay, a shallow microtidal system open to the Gulf of Mexico. Elevations of these major habitat types range from below sea level for seagrass; 0.0-0.6 m msl for salt and fresh marsh; 0.3-1.2 m msl for lowland pine, palm, and hardwood hammocks; 1.2-1.8 m msl for bottomland hardwood and pine flatwoods; and more than 1.8 m msl for pine sandhill and oak associations in the higher elevations approaching 12.2 m msl. The absence of relief contributes to the largely wetland composite of vegetation types.

Zonation of Coastal Marsh and Forest Species and Systems

Land elevation and water depth are key factors controlling habitat type and distribution in this coastal environment. Plot and transect surveys were conducted to derive a conceptual model of community types and succession under different environmental conditions and disturbance regimes. The ability to predict landward transgression of coastal marsh caused by sea-level rise depends on knowledge of the current vegetation distribution linked to land elevation. Vegetation descriptions and elevation data were collected from the forest-marsh ecotone at St. Marks National Wildlife Refuge near Tallahassee, Florida. First-order benchmarks were used to open and/or close transects across the ecosystem ecotone in several watersheds within the refuge boundary; most surveys closed to within 0.254 cm. Station locations were established every 30 m along a given transect from which land elevation and vegetation cover and stature were recorded. Field data were verified by constructing histograms of vegetation distribution with surface elevation. Eleuterius and Eleuterius (1979) used transit surveys and tide gauge recordings to relate the narrow elevation ranges of smooth cordgrass (*Spartina alterniflora*) and needlegrass rush (*Juncus roemerianus*) in a Mississippi marsh to tidal inundation frequency and duration. Using the same methods, I correlated vegetation to elevation in a needlegrass rush marsh at St. Marks National Wildlife Refuge and used the results to predict elevation from vegetation. The results were applicable to four different drainage basins along the coast.

The significance of this field study was the fact that I was able to plot elevation contours within the needlegrass rush marsh landscape by identifying the vegetation on aerial photography and even satellite imagery. Sand flats occupied by batis and pickleweed (*Salicornia*) are highly visible on remote imagery and occur at the same elevation as mean high water (app. 36–40 cm above mean sea level) from predicted tide tables for the area. Also highly visible is the distinct marsh-forest boundary which occurs near the elevation of the highest predicted tides from the same tide tables (60–70 cm above mean sea level). Additional surveys are required to determine whether those two tide regimes (mean high water and level of highest predicted tides) are significant vegetation delineators in other marshes with different tide ranges. Although Stout (1984) provides excellent descriptions of the community structure and elevation profiles of this type of gulf coast needlegrass rush salt marsh, the results of this study go a step further with a spatial analysis and mapping of the elevation contours using the vegetation as a guide.

Development of Landbase Digital Elevation Model

A digital elevation model of the study area was constructed to track the process and pattern of coastal inundation over space and time for projections of sea-level rise. Map information of hypsography and bathymetry of the study area were digitized from a series of coastal map products obtained from USGS 7.5' quadrangle maps (1:24,000 scale) and National Oceanic and Atmospheric Administration (NOAA) hydrographic charts (1:20,000 scale). A standardized algorithm and application program (ARC-INFO/TOPOGRID) was used to construct a high resolution, 30-m, digital elevation model (DEM) (Fig. 6-9). Classified thematic mapper imagery at 30-m pixel resolution of aquatic and terrestrial habitat at a community level was obtained from the Florida Department of Transportation to begin model simulation by vegetative type. Model simulations were generated to predict a likelihood index of habitat change and conversion under flooded conditions for different scenarios of sea-level rise. Model results were displayed in a GIS system and format illustrating habitat type and locations subject to change under altered environmental conditions. The WETLANDS model provides an integrated GIS-modeling framework whereby functional processes of ecological change can be linked with data structures of community and landscape composition.

Coastal Wetland Habitat Loss and Migration

Sea-level rise was simulated based on a series of case projections—low, mid, and high—adopted from the Intergovernmental Panel on Climate Change (1990) for 2000 to 2100 A.D. (Fig. 6-10). At these levels, major portions of the coastal zone in this region will be permanently inundated over the next century, bringing about a migration and loss

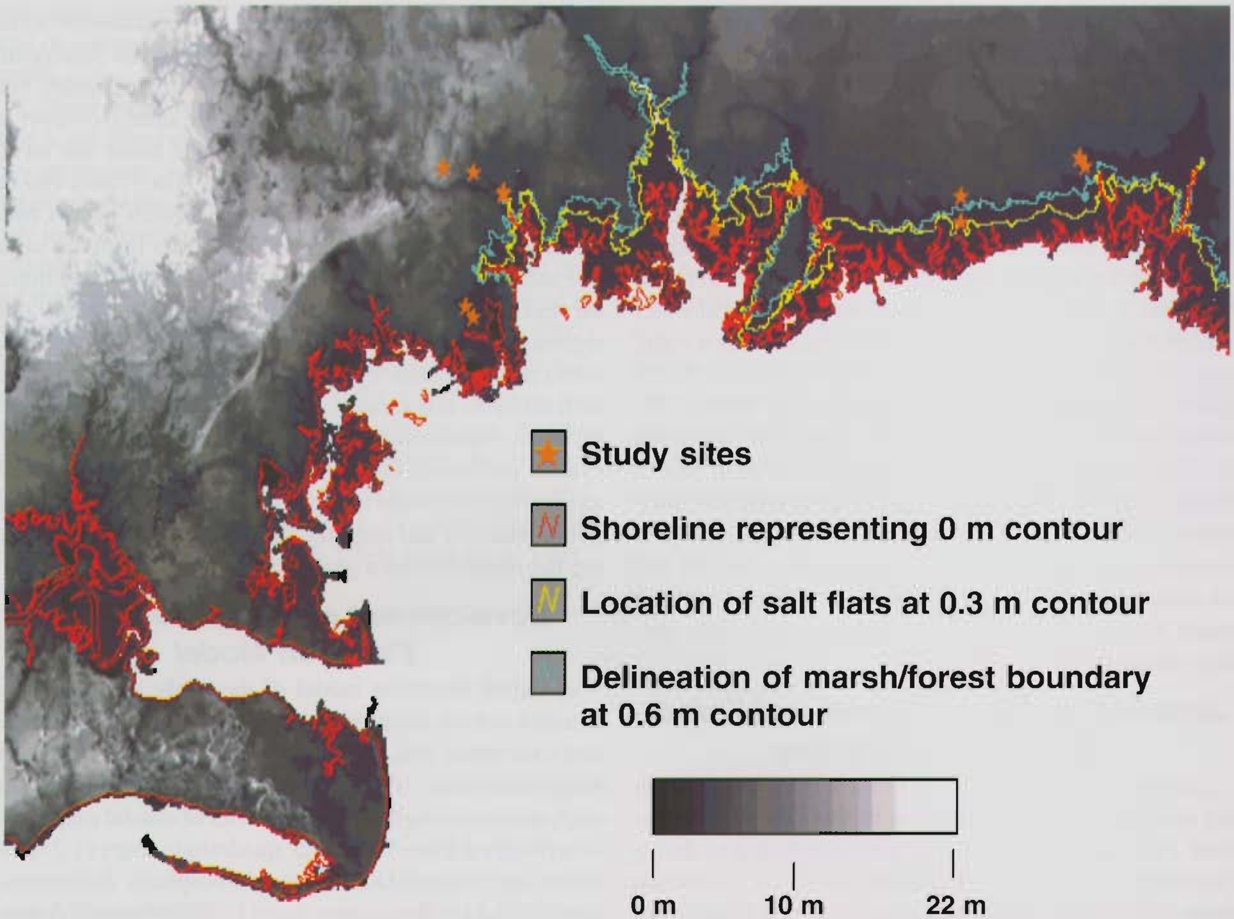


Figure 6-9. Digital elevation model for Big Bend coastal region encompassing St. Marks National Wildlife Refuge south of Tallahassee, Florida.

in the total area and proportion of some habitats. The model incrementally increases the flooding height on an annual basis according to the predicted change in sea-level by year for each sea-level scenario. It determines whether or not habitat conversion and/or loss occur as successive cells from coastal waters exceed the land elevation height of inland terrestrial vegetation and the tolerance of the existing vegetation type for another more tolerant vegetation. Probability functions of species and community tolerance to coastal inundation and elevation have been calibrated from field surveys and are used to predict habitat succession under sea-level rise. The model keeps track of the total number of cells by habitat and net cell loss or gain by year for output.

Because of low relief, model simulations predict significant shoreline changes and inundation of current terrestrial vegetation zones under all three IPCC (1995) sea-level rise projections (Fig. 6-11). Results show that there is a large landbase that will be converted from marsh to open water and forest to marsh. However, due to the slope of the landform, coastal marsh is predicted to increase slightly in land cover as it migrates upslope and replaces existing forest habitat. A significant portion of coastal pinelands standing at or below the 1-m contour will be directly affected by a projected sea level increase of 0.95 m (high) over the next century will be lost (Fig. 6-11). There will be an effective migration of emergent marsh into forested zones though an overall net loss of terrestrial habitat to an open water environment. The use of elevation survey data and surrogate contouring based on ecotone boundaries and tide projections added to the detail and accuracy of interpolating the landform between shoreline and the 1.5-m contour and for predicting habitat loss/gain under increasing sea-level conditions. This modeling approach offers a technological tool for research and policy purposes that allows for effective land and water management, risk assessment, and cumulative impact analysis of wetland systems and landscapes.

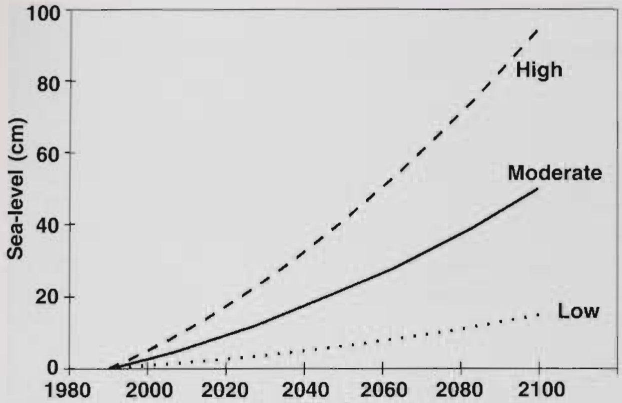


Figure 6-10. Sea-level rise projections and equations for case scenarios of low, moderate, and high cases based on Intergovernmental Panel on Climate Change 1995.

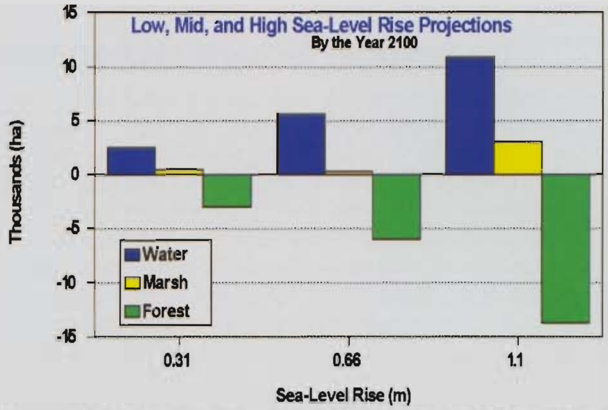


Figure 6-12. Predicted changes of net loss and/or gain of coarse habitat types, open water, emergent marsh, and forest for low, mid, and high sea-level rise (m) projections by the year 2100 as determined from the IPCC 1990.

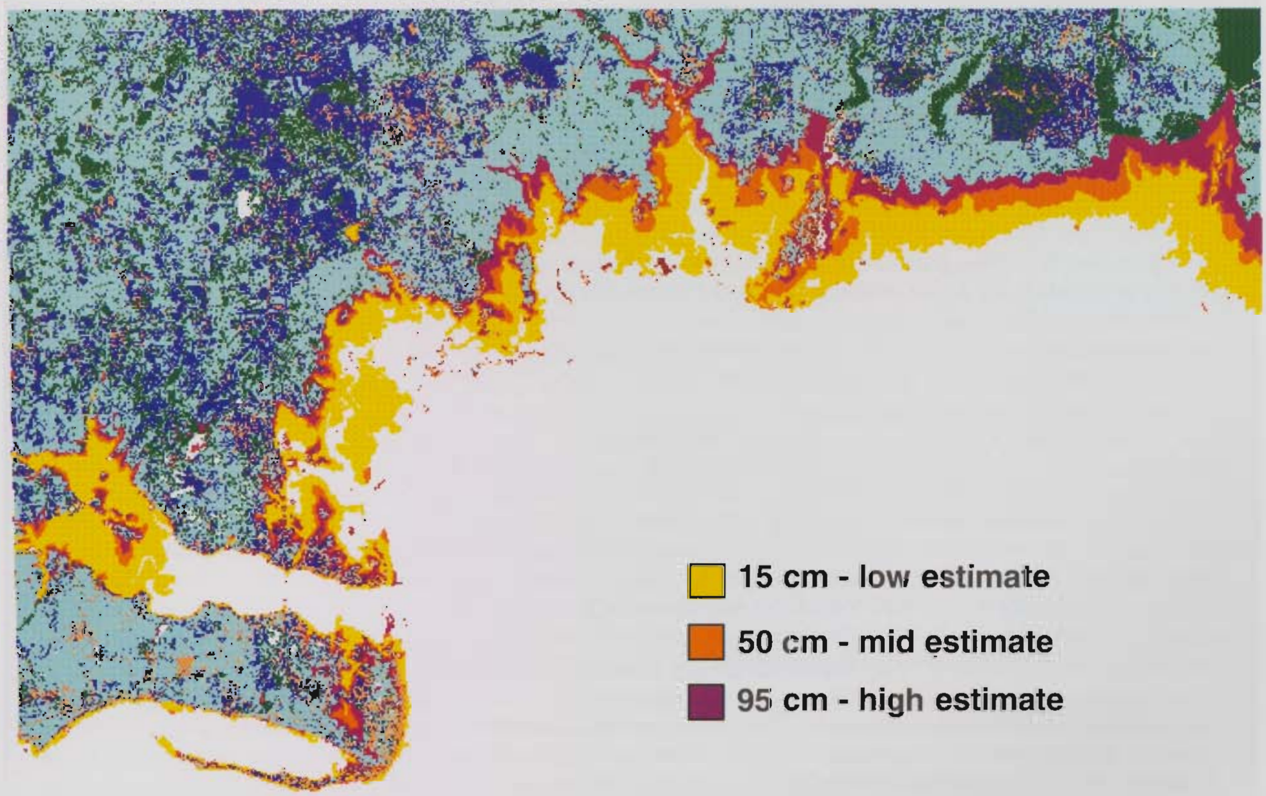


Figure 6-11. Predicted shoreline change and coastal inundation at 15-, 50-, and 95-cm estimates of sea-level rise by the year 2100 based on IPCC (1995) projections.

Ecological Models: what are they and what do they predict?

Ecological models vary in design and detail but all have a common purpose: to predict change in biological response in relation to a change in environment. Simulation models include sets of dynamic functions and relationships that describe the organization or function of a biotic constituent in relation to a set of biotic and environmental conditions. In either case, a model represents a simplification of a real world phenomenon or process, whether of a single cell, single plant, community, or entire biosphere. The response variable and state conditions will vary depending on the domain and the specific processes and problem involved. A typical model may operate within a single domain of biotic organization such as the cell, organ, organism, species, population, community, ecosystem, or biome. For example, ecophysiological models of leaf layer dynamics may share the same domain (i.e., leaf), but vary in detail and complexity depending on what processes are included (i.e., photosynthesis, respiration, transpiration, stomatal conductance, etc.) and the manner in which they are modeled. Individual-based models are perhaps the most common model type that uses the individual organism, plant or animal, as its common unit of study. Ecosystem models are broadly defined model types that predict the state of some collective association of plant and animal populations for a given environmental setting. Ecological models, therefore, may include a suite of model types applicable across a range of spatial and temporal scales and biological domains.

Most ecological models, however, have been designed to predict dynamic behavior at a single point in space through time. With the advent of workstation technology in recent years, models have become increasingly spatially explicit and computationally robust. Global scale modeling of the carbon cycle has advanced to address issues of the role of terrestrial systems in the larger climatic cycle. Geographic information systems (GIS) program applications provide a software approach to managing and querying large data structures for regional applications in a rule-based manner similar to simulation models. Certain individual-based and ecosystem models have been upgraded to operate within a spatially distributed context to address landscape-scale questions of climate change effects on system function and organization.

The Sea Level Affecting Marshes Model (SLAMM) is one example of a map-based simulation model for predicting sea-level rise for given geographic locations. The U.S. Environmental Protection Agency has used this raster-based model to estimate probable losses of coastal wetlands to tidal inundation under given climate change scenarios. The agency has developed multiple versions of the model to investigate sea-level rise implications for coastal wetlands: SLAMM2 (Park et al. 1989), and SLAMM3 (Park et al. 1993). The model simulates wetland conversion and shoreline erosion under varying rates of future sea-level rise (Lee et al. 1992). Land cover type and elevation serve as the primary data layers. Relative sea-level change is modeled as a function of the historic eustatic trend (e.g., 1.2 mm/year), and regional subsidence factors, augmented with a projected sea-level rise scenario. Sedimentation and accretion rates may vary locally as a function of proximity and connectivity to streams and coastal influences. Model results are saved as habitat class maps that are subsequently tabularized to give grid cell counts of habitat change by time period with respect to sea-level height.

Landscape models are in a relatively sophisticated class of ecosystem models that involve spatially distributed operations and connectivity within a landscape that may include multiple ecosystem types and models. Coastal wetland systems consist of a matrix of wetland (and sometimes upland) landform types that are linked by physical and biological processes. Understanding the contribution and process of controlling factors important at different space and time scales demands a landscape approach that combines ecosystem models with a spatial model. The landscape approach provides a more comprehensive framework for integrating the complex interrelationships of changing environmental and biotic factors across spatially and temporally dynamic landscapes. In wetland systems, landscape models simulate projected changes in the physical environment (i.e., hydrology, soils) interdependently with the associated biotic response to forecast resultant changes in habitat distribution and quality. Landscape level applications often use GIS capabilities to construct spatial data structures of initial conditions and to capture spatial and temporal variability of model predictions.

One approach of modeling spatial dynamics is to arrange various ecosystem models and connect them with fluxes of water and nutrients in a manner analogous to the general circulation models (GCM's) currently used in long term climate modeling. This approach has been attempted in only a few cases for ecosystem modeling in the past (Botkin et al. 1972). In general, these past applications were relatively successful, and their rarity is probably due to the size and complexity of the resultant models, as well as the difficulty of assembling the necessary data bases. These limitations are rapidly disappearing with the increasing availability of remote sensing data and computing capability. The Coastal Ecological Landscape Spatial Simulation (CELSS) model is a process-based spatial simulation model of this construction for two marsh-estuarine complexes in south Louisiana, the Atchafalaya/Terrebonne Basin (2,500 km^2) and Barataria Bay (5,000 km^2; Costanza et al. 1990; White et al. 1991). The study areas are represented as an integrated matrix composed of 1-km^2 cells. Each cell contained a dynamic ecosystem simulation model that was habitat-type dependent. The model tracks the projected change in ecosystem type, water level and flow, sedimentation, subsidence, salinity, primary production, and nutrient pools. Model validation was accomplished by matching model predictions for ecosystem type with current and historical maps of habitat distribution. This modeling approach provides a comprehensive framework for synthesizing the direct and indirect, spatial, and temporal responses of coinciding natural and human-induced factors affecting coastal ecosystems. Model applications included evaluations of surface water management and climate change effects of rising sea level.

Reconstructing Hurricane History and Impact

Hurricanes are episodic climatic events of formidable force and destruction to both developed and undeveloped areas. The regularity and severity of tropical storms are major determinants controlling ecosystem structure and development for coastal forests worldwide. Long-term monitoring of hurricane impact and ecosystem recovery is needed to understand how some coastal systems adapt and respond to large-scale disturbances. Tree-rings have traditionally been used to reconstruct past climate and disturbance phenomena, including drought, fire, floods, insect outbreaks, earthquakes, and volcanic eruptions. A few studies have addressed the effects of hurricane impact on subsequent forest growth and succession. Pillow (1931) associated compression wood development in longleaf pine with hurricane injury. Doyle and Gorham (1996) and Gorham (1992) found missing rings and abrupt growth changes in years immediately following major hurricanes among pines along the gulf coast of Alabama and Mississippi, while a study by Merrens and Peart (1992) noted increased radial growth of hardwoods in New Hampshire following a 1938 hurricane. Akachuku (1993) reported differences in crown morphology and bole shape as a function of 50 years of regrowth following hurricane damage among red pines (*Pinus resinosa*) at Harvard Forest in Petersham, Massachusetts. Using a computer model of forest growth and succession, Doyle (1981) showed that hurricane frequency plays a major role in maintaining the species diversity and structural characteristics of insular forests of the Caribbean.

Field surveys have been conducted throughout the Gulf of Mexico region to establish baseline data on forest response to hurricane impact and history. Aerial videography, permanent plots, and tree-ring analyses have been used to assess the degree and expression of hurricane damage and recovery for more than 20 coastal parks and preserves along the gulf coast areas of Louisiana, Mississippi, Alabama, and Florida. Spatial analyses of these data show a pattern of non-random windthrow orientation and stem class distributions that are related to the size, path, and intensity of past hurricanes, and more recently to Hurricane Andrew (1992). A spatial simulation model of hurricane abiotics, HURASIM, was applied to reconstruct chronologies of hurricane windforce and vectors for each site derived from historic tracking data of North Atlantic tropical storms including Hurricane Andrew. The model generated a matrix of storm characteristics (i.e., quadrant, windspeed, and direction) within discrete spatial units and time slots over the period of Hurricane Andrew's passing and for all previous storms specific to each study site. The HURASIM model output was correlated with ground and mapped data to construct data tables of damage probabilities by site and species and to determine critical windspeeds and vectors for each storm's path. Tree-ring analyses of past growth demonstrated significant departures from expected growth trends coincident with hurricane events. Sites and events demonstrating growth departures were correlated with storm proximity, intensity, and assymetry with respect to windspeed. Impacts could be detected as far as 96.5 km per hour from the eye when windspeeds still exceeded 177 km per hour. This study provides a baseline of the spatial extent to which hurricanes can affect coastal environments depending on storm strength and orientation and on forest conditions. Empirical relationships drawn from this work have been incorporated into simulation models of forest growth and succession for mangrove, pine flatwood, and bottomland hardwood systems of the gulf coastal region.