Landscape Change in Yucatan's Northwest Coastal Wetlands (1948-1991)

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Abstract

A planimetric analysis was made of aerial photographs from 1948, 1979 and 1991, to observe changes in and loss of vegetation in the region between the ports of Progreso and Sisal, Yucatan, Mexico. This analysis shows that in the 43 years between 1948 and 1991, 174.4 km^2 of the region's vegetation has been altered, with a 4.05 km^2 annual absolute rate of change. The study area has been influenced by: 1) road construction; 2) opening of the Yucalpeten harbor; 3) population growth; 4) saltwater intrusion through coastal sandbar breaches; and 5) freshwater spring sedimentation. Some chronic, anthropogenic stressors can decrease the natural recovery process during rainy periods. The continuing restoration activities in the region are commendable as they improve coastal wetlands' ability to cope with stress, and control energy loss. An educational program should be developed that provides community members the opportunity to understand and conserve the environment.

Keywords: *landscape change, cyclic succession, human activities, mangrove forest, coastal zone, Mexico*

Introduction

Coastal wetlands are self-maintaining landscape units that are responsive to long-term geomorphological processes and have continuous interactions with contiguous ecosystems. They are open systems with respect to both energy and matter (*i.e.*, they receive freshwater and nutrient inputs, and export organic matter toward the sea) and thus can be considered "interface" ecosystems, coupling upland terrestrial and coastal ecosystems (Lugo and Snedaker 1974, 39-64). Mangrove swamps are the most common type of wetland along the coast of the Yucatan Peninsula (Olmsted 1993, 637-677), and have played an important part in the local economy for thousands of years. They constitute a reservoir and refuge for many unusual plants and animals, as well as supporting commercial and recreational fisheries, and serving many other direct and indirect functions (Hamilton and Snedaker 1984).

Of 569 sites on the Ramsar list of wetlands of international importance, at least 84% are undergoing ecological changes, which are principally related to changes in the hydrologic regimen due to socio-economic activities (Dugan 1992). In Yucatan, one of the most severe problems that affect coastal wetlands are the construction of highways, railroads, dams, and ports (Paré and Fraga 1994). Presently, the government of the State of Yucatan is working on an Environmental Restoration and Improvement Program at the ports of Progreso and Sisal. This program includes the clearing of freshwater springs, culvert construction, natural drainage system reclamation, highway bridge construction, and community training involving information exchange.

In the present study a planimetric analysis was made of aerial photographs from 1948, 1979 and 1991 to estimate vegetation type changes in a 250 km^2 coastal region between the ports of Progreso and Sisal. A bibliographic review and empirical data are included to describe environmental characteristics and human activities. These descriptions are used to evaluate the main factors controlling coastal landscape dynamics, wetlands stress, succession patterns and mangrove tree mortality, in order to develop an hypothesis explaining local phenomena. It was anticipated that the coastal wetlands landscape in Yucatan has changed not solely because of human activities, but due to a combination of natural and anthropogenic stressors. However, human stressors can weaken wetlands, and make them more susceptible to further natural stress.

Study Area

The study area is located on the northwest coast of the Yucatan Peninsula (Figure 1), between the ports of Progreso

(21˚ 17' 18" LN and 89˚ 39' 15" LW), and Sisal (21˚ 10' 06" LN and 90˚ 01' 30" LW). According to Garcia (1978), this zone has an arid and semi-arid climate (BSo(h')w(x')), with an average annual temperature variation between 25.5 and 26.5˚ C, and total annual precipitation between approximately 450 to 580 mm. Evaporation is the dominant hydrological process in the region, with values of 1959 mm per year.

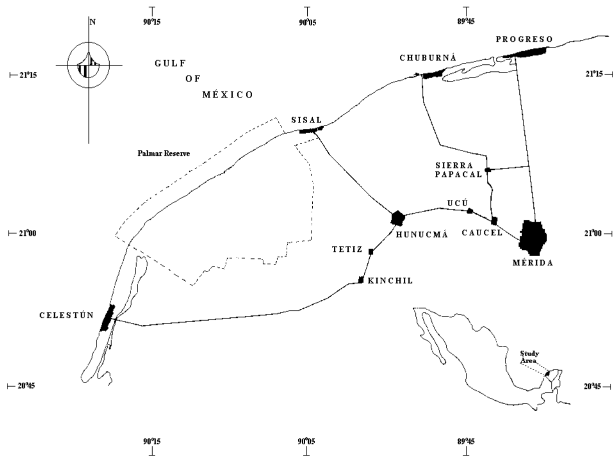


FIGURE 1 .- LOCATION OF STUDY ZONE

This area is formed by marine Tertiary carbonates that have been subjected to extensive mechanical and chemical dissolution. Holes and cavities have been formed by rainfall infiltration and sea level fluctuations, creating a highly permeable aquifer. There are no surface streams and the high degree of karstification permits rapid infiltration. Collapse of cavities in the substrate produces the dolines and coastal springs known locally as *cenotes*. An extensive freshwater lens exists above a salt-water intrusion zone that penetrates more than 40 km inland. This lens is confined along the north coast by the coastal aquitard, a thin, planar, nearly impermeable calcareous layer. The interaction of saltwater inputs from the ocean and freshwater inputs from the confined underground aquifer forms the natural hydrology of wetlands (Perry et al 1989, 818-821). In the study area freshwater flow, from springs, controls the salinity gradient. Mangrove is a generic term referring to communities composed of trees usually not more than 8-12 m tall that permanently occupy coastal areas, or periodically inundated areas, where the main physiological trait is the plants' ability to grow in a regime of fluctuating salinity. The mangroves within the study area are classified in four types:

Low swamp mangrove. This mangrove occupies the lowest parts of the basin, located nearest the coastal sandbar. It tends to grow as shrubs, with heights of 3 to 5 m, and to form islands of vegetation within the swamp. It is inundated almost year-round, though principally during the fall rainy season, when inundation reaches its highest level and is affected by the marine tidal flux. This mangrove can grow in soils with high salinities, such as areas mixed with salt flats. Due to the swamp hydrologic dynamic, and the fact that water flow in these areas parallels the coast, this mangrove is affected by flow alterations caused by road and port construction that interrupt natural water flow and increase sedimentation. The principal species in this community is *Avicennia germinans*, followed in importance by *Rhizophora mangle*, the latter tending to die rapidly as it is apparently more affected by habitat alteration. Some marine grasses such as *Thallasia testudinum* and *Halodule wrightii*, and macroalgaes such as *Enteromorpha oerstedi*, are habitats of a great variety of resources as shrimps and fishes larvaes.

Shrub mangrove. Present in zones with severe growth and development limitations, this mangrove develops on marl soils (calcium carbonate and clay). It is temporally deluged, and reaches its maximum water level after the rainy season. The salinity regimen varies according to its relation to nearby freshwater, brackish or saline environments. These mangroves, *Rhizophora mangle* and *Avicennia germinans*, vary in density from extremely dense and impassable to dispersed. In extreme cases, the density is so low that they form savanna communities, dominated by grasses (Gramineae and Ciperaceae). They tend to grow as shrubs, with heights of 1 to 1.5 m, rarely surpassing 2–3 m, and occupy intermediate parts of the basin, forming a wide band between the low swamp and high basin mangrove.

High basin mangrove. A low, very dense arboreum community, consisting basically of *Conocarpus erecta*, *Laguncularia racemosa* and occasionally *Avicennia germinans* forms this. Since it is found in internal basin areas, it can form transitional zones (ecotones) with the inland low flooded or low dry forests. It is possible that this mangrove does not have marine influence, except in special conditions such as those during strong storms.

Petenes (Hammocks). One of the most notable characteristics of the Yucatecan coast, is the presence of islands of vegetation commonly called *petenes*. The word *peten* comes of the Mayan and means high fields or plains. The *petenes* exist due to a soil level increase relative to adjacent areas. This increase controls the inundation period and permits the growth of mangrove and forest plants. All *petenes* within the study area have one or more springs, generally in their center. *Peten* vegetation is very diverse and can reach heights of more than 20 m. It consists of species such as *Rhizophora mangle, Laguncularia racemosa, Avicennia germinans, Typha dominguensis, Cladium jamaicencis, Manilkara sapota, Ficus tecolutensis, Sabal yapa, Bravaisia tubiflora,* *Acrostichum aureum* and *Hymenocallis littoralis*, among others, and is mainly intercalated in the scrub mangrove.

Low flooded forest and low forest with savanna. Found on the southern border of mangrove vegetation and related coastal landscape, the low flooded forest is located in the transition zone between the low deciduous and mangrove forests, with seasonal freshwater inundation and good drainage. This sort of vegetation forms a rich mosaic with trees reaching to 12 m in height. Species in this forest include *Manilkara sapota, Brosimum alicastrum, Thevetia sp, Plumeria sp., Annona glabra, Bucida buceras, Metopium brownei, Haematoxilum campechianum, Conocarpus erectus* and *Thrinax radiata*. Inside this forest there are aquatic plants such as *Typha dominguensis* and *Nymphaea ampla*. Seasonally inundated with fresh to brackish water, the savanna has fewer species, with grasses such as *Eleocharis cellulosa* and *Cladium jamaicencis* and other Gramineae and Cyperaceae dominating, and isolated elements of *Crescentia cujete* and *Byrsomina crassifolia.* It is intercalated with some scrub mangrove trees (Olmsted 1993, 637-677).

Socioeconomic Development

The northwest coast of Yucatan was settled by the Maya long before arrival of the Spanish, though significant development did not begin until the mid-1800's (Table 1). The major economic activities in this area were salt production and fishing, activities still quite important to Mayan descendents. Modern coastal development, and especially port development, was originally stimulated by commerce such as the export of goods such as *henequen* or sisal (Meyer-Arendt 1993, 103-117).

During most of the Colonial period, the city of Campeche, approximately 200 km southwest of Mérida, was the principal seaport for the Yucatan Peninsula. Beginning in the first decade of the 16th century, the fishing settlement of Sisal, approximately 50 km northwest of Mérida, was the official port of the State of Yucatan. Sisal saw the beginnings of *henequen* fiber export, and its history was strongly linked to this industry's vicissitudes. During the height of *henequen* production, the coast's population was concentrated at Sisal. However, Sisal was frequently inaccessible during the rainy season, and as the export market for *henequen* increased in the 1830's, a new port, Progreso de Castro, displaced the port of Sisal. Progreso was established in 1856 as a site closer to the state capital at Mérida.

At the end of the 19th century a crude 32-km road from Mérida to the new settlement was constructed, and the first railroad service between Mérida and Progreso began (Meyer-Arendt 1991, 327-336). The first public notice of human activities' environment impacts on Yucatecan coastal wetlands was published in the article called "The Health of Progreso City and Port" by Arturo Schafer in *El Horizonte* newspaper (published February 26, 1893 at Progreso Puerto; -R. Frías Bobadilla Hemerotec). According to the article "...[T]he sedimentation process that the Progreso Puerto swamp is suffering, due to the railroad, results in a flow obstruction that causes a water level decrease related to the high evaporation in this very hot climate... [and] promotes palustrine diseases... [I]t is necessary and urgent to construct more culverts to allow for water flow and, open two canals in the sand barrier to obtain incoming sea water and promote the movement of water masses — If not, there will be more problems in the water healt" (Batllori et al 1993).

Although the primary function of the railroad was to export *henequen*, Mérida residents quickly discovered Progreso's beaches, and wealthy families soon began to build summer homes. In 1928, the Mérida-Progreso highway was paved, and in 1947, the 2 km-long concrete wharf at Progreso was completed. Shorefront urbanization extended to the east and west of Progreso. In the middle of the present century the Mérida-Hunucmá-Sisal highway was paved. Sisal continues being a quiet port, engaged in fishing for local consumption, wood cutting and coconut cultivation. In the decades following the highway's paving, sport hunting (especially for wild ducks) by hunters from outside the region increased, with a large number of the local population serving as guides.

In 1968 the Yucalpetén harbor was opened for the Progreso fishing fleet as a solution to lack of adequate docking space, as well as for protection from storm waves. The port was created in the back barrier lagoon, and forced the relocation of the coastal highway to Chelem. A channel entrance was excavated through the coastal sandbar, and jetties built to prevent sedimentation. Yucalpeten harbor provides a base for the Mexican Navy, the Progreso fishing fleet, and a growing seafood processing industry (Meyer-Arendt 1993, 103-117).

As the *henequen* industry faltered in the 1970's and 1980's a huge population displacement occurred from inland, *henequen*-growing areas towards the coast. In 1980, Progreso's population was 28,902, with an annual growth rate of 4.8%. In 1988 the population grew to 41,686, with 6,836 permanent residences. This immigration-based population growth has resulted in the expansion of urban areas into the swamp as immigrants are forced to settle on swampland filled with garbage, sand, and stones. This on-going trend will be one of the contributing factors to the gradual deterioration of vegetation and wildlife in coastal ecosystems (Paré and Fraga 1994).

However, these same trends - the flow of capital to the port, land communication with the interior, the government policy of encouraging migration of *henequen* farmers toward the coast - have not produced a real demographic revolution in Sisal. The General Censuses of Population of the State of Yucatan for 1970 and 1990 show a growth from 711 to 1,460 inhabitants in Sisal. Vacation home development in the area has continued throughout the 1990's, creating an urban area stretching from Chuburná Puerto east to Chicxulub Puerto. Fishing, hunting, tourism, salt extraction, agriculture and cattle, are the main economic activities in the area between Sisal and Chuburná Puerto. In Progreso, commercial fishing and the ultramarine trade are the principal economic activities, with both the fishing and building infrastructure industries being well-developed. Fishing is the most important activity at these two ports, though in the last decade development of industries such as shipyards, packing plants, tourism, and human settlements have increased considerably. All these activities introduce contaminants into the swamp, and deposit sewage in absorption wells constructed at the surface, near the wetlands.

At the present time, hunting has diminished drastically, salt exploitation is stagnant, commercial fisheries are overused and only the swamp resources such as shrimps, crabs, fishes and mollusks are used mainly by old people, women and children, during all the year and specially during the north wind season. In 1995 a Governmental Restoration Program started to enhance coastal wetlands' deteriorated functions.

Table 1. Human activities and hurricanes between Progreso and Sisal, Yucatan. (Sources: Gobierno del Estado de Yucatan, 1959; Meyer-Arendt, 1991; Paré and Fraga, 1994).

1566	First construction of Sisal road, with five bridges
1810	Opening of Port of Sisal
1811	Construction of Sisal wharf
1856	New port construction begun, at Progreso de Castro, 32 km from Merida
1861	Crude road constructed from Mérida to the Port of Progreso
1870	Customs house transferred from Sisal to Progreso
1881	First train service begun between Mérida and Progreso
1900	Mérida residents discover beaches; wealthy families begin to build vacation homes
1903	Hurricane (?)
1916	Ditch cut through coastal sandbar at Progreso to allow lagoon waters to drain into the sea
1928	Mérida-Progreso highway paved
1944	Hurricane (?)
1944	Second ditch dug through coastal sandbar at the west end of Progresso to drain lagoon waters
1947	2 km-long concrete wharf at Progreso completed
1948 aerial images	
1959	Hunucmá-Sisal highway paved
1964	Series of rock and timber groins installed in Progreso
1966	Hurricane Ines
1967	Hurricane Beula
1968	Harbor for Progreso fishing fleet opened, allowing sea water entrance
1970-1980	Continuing vacation home development; an urban strip emerges from Chuburná to Chicxulub Puerto; population growth due to immigration results in expansion of urban areas into swamps.
1974	Hurricane Carmen
1979 aerial images	
1985	Hurricane Juan
1987	Construction of Sisal safe harbor
1988	Hurricane Gilbert opens Chuburná and Carbonera breaches in coastal sandbar between Chuburná and Sisal, allowing sea water entrance
1991 aerial images	
1991	El Palmar Reserve Wetland Restoration Program begun with clearing of coastal springs
1994	Chuburna breach, created by Hurricane Gilbert, begins to serve as harbor
1995	Hurricanes Roxanne and Opal
1995	DUMAC builds dam in Chuburná harbor to prevent salt water intrusion
1995	Progreso Wetland Restoration Program begun with clearing of coastal springs
1997	Mangrove recovery near Dzula and Elepeten, between Chuburná and Sisal
1997	Whole Coastal Zone Restoration Program begun with clearing of coastal springs, and construction of bridges and culverts

Method

Black and white aerial photographs were analyzed for the area between Sisal and Progreso from 1948 (1:30,000; Aerofoto, S.A.), 1979 (1:80,000; National Institute of Statistics, Geography and Informatic/INEGI) and 1991 (1:75,000; INEGI). The 1948 photographs were reduced in scale from 1:30,000 to 1:79,000. The scale verification was done using the equation

$z = (y*s)/x$, where: z = aerial photograph scale, x = distance between two points on the photograph, y = distance between two map points, and s = map's scale (Sobrevila and Bath 1992).

Photointerpretation was made using a stereoscope and 1:250,000 scale thematic maps for geology, topography, hydrology, soils and vegetation (INEGI), in order to recognize features such as coastline, urban zones, lagoons, roads, geomorphologic characteristics, and vegetation physiognomy. Annotations were made using acetate sheets, and aerial photograph north orientation determined by their superposition upon the maps.

Batllori's landscape classification (1995) for the northwest coast of Yucatan was modified for the present study as follows:

Impacted mangrove with salt flats (IM): biogenic swamp, karstic, very low elevation(<1 m), permanently inundated with tide regimen, salty, with deep, organic solonchak and histosol soils, strong hydromorphism, low swamp mangrove vegetation and salt flats, degraded.

Zone of petenes and mangrove forest (ZPM): biogenic swamp, cumulative, very low elevation (<1 m), seasonally inundated, with deep, organic solonchak and histosol soils, partially salty, with aquatic vegetation, scrub mangrove and mangrove with dry forest elements.

Low forest with savanna (LFS) and Low flooded forest (LFF): partially denuded karst, seasonally inundated, with shallow rendzina soils; the LFS having solonchak soils, with savanna elements and scrub mangrove; and the LFF having histosol soils, forest vegetation, aquatic vegetation and high basin mangrove elements.

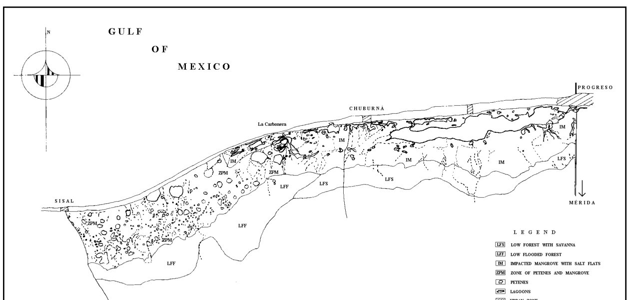


FIGURE 2 - COASTAL LANDSCAPE 1948

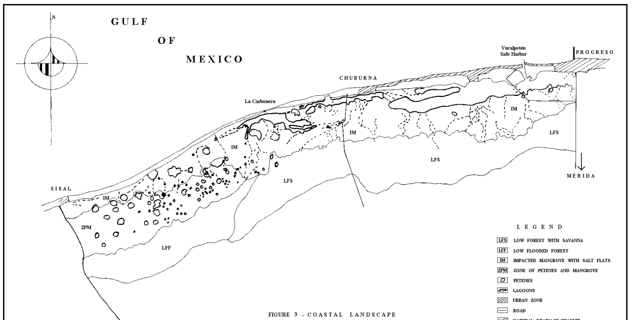


FIGURE 3 - COASTAL LANDSCAPE 1979

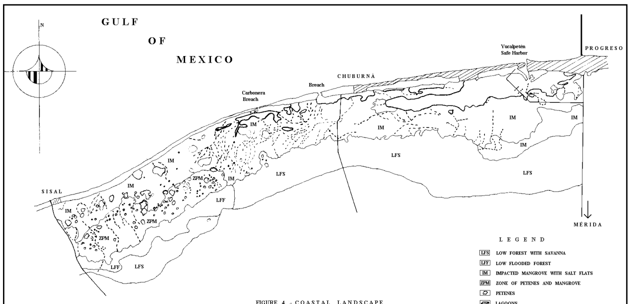


FIGURE 4 - COASTAL LANDSCAPE 1991

Each unit area was calculated using a planimeter, their total area being 250 km^2 (Figures 2, 3, and 4). Finally, a field verification and a bibliographical review were made to compare landscape unit features. Maps were digitized and edited using the Corel Photo Paint v.4 program.

Results

Landscape Change

During the 43 years between 1948 and 1991, 174.4 km^2 of the 250 km^2, or almost 70%, of the total study area have changed vegetation type. This an alteration rate of 4 km^2/year (Tables 2-5). Of the four landscape classifications, two have increased in area, and the remaining two have decreased. The *Low forest with savanna (LFS)* has expanded toward Sisal, with a total increase in area of 52.1 km^2, and the *Impacted mangrove with salt flats (IM)* has increased 35.2 km^2 in area, and now extends from Progreso to Sisal, threatening El Palmar Reserve. The *Low flooded forest (LFF)* has contracted 31.07 km^2 in area, and the *Zone of petenes with mangrove forest (ZPM)* has decreased by 55.8 km^2. The most alarming consequence of this vegetation type change has been the loss of some *petenes*, and the geohydrological alteration of others via spring sedimentation.

Table 2- Landscape surface (km^2) between the ports of Progreso and Sisal, Yucatan, Mexico

	1948	1979	1991
LFS	31.90	74.07	84.0
LFF	43.27	29.15	12.0
IM	95.74	111.00	131.0
ZPM	79.43	36.00	23.6
Total	250.30	250.20	250.6

LFS = Low forest with savanna; LFF = Low flooded forest; IM = Impacted mangrove;
ZPM = Zone of *petenes* and mangrove

Table 3.- Relative landscape change (%) between the ports of Progreso and Sisal, Yucatan, Mexico

	1948	1979	1991
LFS	13	30	34
LFF	17	12	5
IM	38	44	52
ZPM	32	14	9

LFS = Low forest with savanna; LFF = Low flooded forest; IM = Impacted mangrove;
ZPM = Zone of *petenes* and mangrove

Table 4- Landscape change (km^2) between the ports of Progreso and Sisal, Yucatan, Mexico

	1948-1979 (31 years)	1979-1991 (12 years)	1948-1991 (43 years)
LFS	+42.17	+9.93	+52.10
LFF	-14.12	-16.95	-31.07
IM	+15.26	+20.00	+35.26
ZPM	-43.43	-12.40	-55.83
Absolute	114.90	59.28	174.46

LFS = Low forest with savanna; LFF = Low flooded forest; IM = Impacted mangrove;
ZPM = Zone of *petenes* and mangrove.

Table 5- Landscape change rate (km^2/year) between the ports of Progreso and Sisal, Yucatan, Mexico

	1948-1979 (31 years)	1979-1991 (12 years)	1948-1991 (43 years)
LFS	+1.36	+0.83	+1.22
LFF	-0.33	-1.41	-0.72
IM	+0.49	+1.66	+0.82
ZPM	-1.41	-1.01	-1.29
Absolute	3.59	4.94	4.05

LFS = Low forest with savanna; LFF = Low flooded forest; IM = Impacted mangrove;
ZPM = Zone of *petenes* and mangrove.

During the 31 years between 1948-1979, the greatest change in vegetation type occurred in the low forest with savanna, and the zone of *petenes* with mangrove. This may have been due to natural phenomena such as hurricanes and droughts, and human activities such as the opening of Yucalpeten harbor. In contrast, the 12 years between 1979 and 1991, saw an even greater alteration in vegetation type coverage, possibly due to socioeconomic development such as the opening of harbors, population increase, infrastructure, and tourism in Progreso, Chuburná and Sisal, and natural phenomena such as hurricane Gilbert on 1988. This increase cannot be attributed to a single factor, but is more likely the result of interaction between natural and human impacts (Jiménez et al 1985, 177-185).

Discussion

Successional Patterns

Chapman (1976) proposed the idea of cyclic succession as a more realistic way of conceptualizing coastal ecosystem succession. A cyclic succession is when two or more stages in a mangrove succession oscillate under the influence of environmental stressors such as hurricanes, the “cyclic stage” of the succession being maintained by the stressor’s recurrence. According to Odum (1967, 81-138) coastal systems have characteristics as a result of periodic setbacks caused by acute but predictable environmental stressors, and exhibit a “pulse stability”.

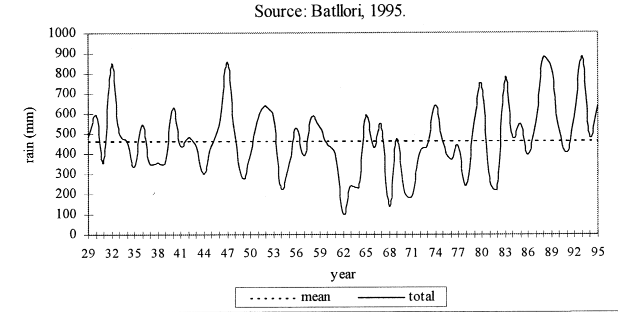
As long as each other and not non-mangrove species replace mangrove species, the mangrove ecosystem is the steady-state system for the area (Lugo 1980, 65-72). Thus mangrove forests that maintain themselves in spite of cyclic events with frequencies of 50-100 years should be considered steady-state systems. Since mangrove ecosystems can usually achieve maturity (maximum biomass) in 20-30 years (Lugo and Snedaker 1974, 39-64), this approach allows ample time for the systems to be viewed as steady state in that they are the optimal and self-maintaining ecosystems in low-energy tropical saline environments. In such a situation, high rates of mortality, dispersal, germination, and growth are necessary survival tools (Lugo 1980, 65-72).

Zonation is a response of the mangrove ecosystem to external forces rather than a temporal sequence induced by the plants themselves. The most important external factors, or stressors, to mangrove function are: tidal flushing, which removes stored potential energy in the form of detritus and dissolved organics; storm tides and waves, which may cause excessive siltation or erosion; periodic hurricanes or storm winds, which disrupt system structure; and climate. The latter influence is important as it regulates freshwater availability, nutrients from overland runoff and springs, soil, and temperature. In arid environments excessive evaporation concentrates salts in the soil, and terrestrial inputs are reduced (Cintrón et al 1978).

Temporal variations in these factors include tides, rainfall, runoff seasonality, and hurricane periods. These may have frequencies ranging from hours to decades. Superimposed on these are cycles with longer periodicities such as regional sedimentary cycles, and sea level changes. Cyclic rainfall patterns and hurricanes may act as succession speed and direction regulators. Rainy periods are associated with lower soil salinities and mangrove zone expansion, whereas drought periods result in high soil salinities, mangrove mortality, and salt flat expansion (Jiménez et al 1985, 177-185).

Batllori (1995) describes rainfall patterns at Progreso, Yucatan, showing that there have been years of high and low precipitation closely associated with wet and dry periods. For example, between 1953 and 1982 there was a dry period which may have effected vegetation change (Figure 5).

Figure 5.- Pluvial Precipitation, Progreso, Yucatan (1929-1995)
Source: Batllori, 1995.



Massive tree mortality is a response to rapid environmental change, and affects all size classes (Jiménez et al 1985, 177-185). This occurs in addition to normal tree mortality, which is density dependent, and usually occurs in the smaller diameter size classes. Diseases and other biotic factors do not appear to be primary causes of massive mangrove mortalities. Rather, these factors appear to attack forests weakened by changes in the physical environment. Mangrove environments are dynamic and cyclic, and mangrove associations adapt to such environments by both growing and dying quickly.

As ecosystems develop toward steady state, they gain information that, in part, allows them to anticipate fluctuations in their environments. At the ecosystem level an event may cause mortality in certain sectors of the system, but the system as a whole may be able to adapt (Margalef 1975, 151-160). For example, hurricanes kill mangrove trees, but they are essential for mangrove forest survival (Cintrón et al 1978). Hurricanes are natural factors causing spring sedimentation and a subsequent reduction in freshwater influx that affects ecosystems through changes in water and soil salinity, lowering of soil pH, and excessive siltation (Lugo and Snedaker 1974, 39-64). In mangrove ecosystems, hurricanes cause death by direct mechanical action including trunk breaking, bark loosening, and severe defoliation, and indirect effects such as flooding and siltation (Jiménez et al 1985, 177-185). These factors can increase wetlands' physiologic stress level and induce changes in vegetation distribution and types, usually from low flooded forest to savanna (Zizumbo 1986).

Between 1900 to 1997, hurricanes crossed near the northwest coast of Yucatan (Table 1), resulting in several breaches in the coastal sandbar which caused seawater influx and sedimentation in the mangrove forests. In 1988, Hurricane Gilbert opened several breaches, among them the Chuburná, Carbonera, and El Palmar breaches between Celestún and Progreso. In fall 1991 the El Palmar breach was closed by natural phenomena related to the north wind season, and a strong deposition of seaweed and seagrass that formed a natural sand trap. The Chuburná breach began to function as a harbor, but in 1995, Ducks Unlimited of Mexico, A.C. (DUMAC) built a dam behind this harbor to prevent salt water influx. Presently, the Yucalpetén harbor, and Carbonera breach are still open, increasing water and soil salinity. Hurricane-induced sedimentation is likely the cause of a high soil level area within the swamp between the Carbonera breach and Sisal that diminishes the flooding period (SMAD/CDB,1996).

According to Craighead and Gilbert (1962), after hurricane Donna in 1960, Florida's mangrove mortality ranged between 25 and 75 % over some 384 km^2. The speed of successional recovery after a perturbation should vary among different mangrove types, and depends on the degree of matter and energy exchanged with nearby ecosystems and growth conditions at each site. For example, under riverine conditions primary productivity is high, and succession after a perturbation is rapid. After hurricanes these forests can recover in about 20 years (Lugo and Snedaker 1974, 39-64). However, scrub forests have very low primary productivity, grow slowly, and thus succession after a perturbation is slow (Cintrón et al 1978).

Hurricanes may shape the structure of forest as well as limit its overall development. Odum (1970, 191-289) notes that forests in the hurricane zone do not have emergent trees (*i.e.*, the crown surface is relatively uniform), unlike comparable forests outside the geographical influence of hurricanes. In Panama, for instance, mangrove forest biomass can attain levels approximately two times those reported for Florida and Puerto Rico, which lie within the hurricane zone. The probable mean hurricane frequency in Florida and Puerto Rico is between 20 and 24 years (Lugo et al 1975, 335-350), and mangroves in both areas are reported to reach maturity at around 20-25 years. Given this, maximum biomass and structure development are probably limited by hurricanes, all other environmental constraints being equal. Expected recovery time for mangroves destroyed by hurricanes is about 20 years, though Westing (1971, 893-898) suggests that recovery may take much longer.

Spatial differences are the result of mangrove forest location, the topographic position of the system delineating growth conditions (Lugo and Snedaker 1974, 39-64). The relative influence of marine and terrestrial factors changes with proximity to the sea. For example, soil salinity is higher in basin forests and arid environment scrub mangroves, and consequently these forests have lower transpiration rates (Lugo et al 1975, 335-350). Forest stature or complexity can be used as a reliable indicator of how favorable conditions are for mangrove growth, there being an inverse correlation between soil salinity and forest height (Cintrón et al 1978).

According to Thom (1967, 301-343), mangrove forest zonation and structure in Tabasco, Mexico, are responsive to sea level changes, and mangrove zones can be viewed as steady-state zones migrating toward or away from the sea in response to sea level changes. He postulates that mangrove zones are responsive to geomorphological changes in the regions where they grow. Substratum and water are important zonation-controlling factors, and each specie finds its place, given its salinity tolerance range, within the environmental gradient created by the substratum and water flow regimes. Finally, he suggests that salinity is simply a competition eliminator and not a zonation-determining factor. This is likely true in this region of México, as the Grijalva and Usumacinta river systems introduce large quantities of fresh water into the area, maintaining salinity at low levels most of the year.

In contrast to natural cycles, human impacts are unpredictable events that interfere with natural ecosystems because they do not necessarily follow recognizable patterns, and do not operate long enough to allow adaptation development.

Natural and Anthropogenic Stressors

Stressors have been defined as any factor or situation that forces a system to mobilize its resources and expend energy to maintain homeostasis (Seyle 1956). Stressors are energy drains because they involve diversion of potential energy flows that might otherwise be used for useful work in a system (Odum 1967, 81-138). An environmental change that reduces total energy flow results in a rapid decrease in structural complexity, particularly if the system loses its main energy source. Systems with high organic productivity but low species diversity and complexity usually export their production to other systems and, in so doing, lose the capacity to diversify. This is certainly true of mangrove forests and other systems stressed with high organic matter loads. These systems' apparent stability is due to uninterrupted input of certain energy sources that represent a significant fraction of their total energy. Stability is a function of stable energy input, and in most systems stability disappears with diversion of the main energy source.

In Yucatan, freshwater springs (*petenes*) are an important energy source responsible for the mangrove's high production levels. Through flushing of toxins and nutrient transport, these springs' provide energy to the system. It may be that in mangrove forests such as *petenes*, the low, stable temperature, high nutrient input and low salinity allow the system to expend energy on increasing diversity (Batllori 1995). For example, in the low swamp mangrove and scrub mangrove greater salt concentrations were detected between 1991 and 1996. Average salinity during this period was 31.8 parts per thousand (ppt) with a variation range of 96 ppt, whereas the *petenes* had an average of 1.47 ppt with a 2 ppt variation. Average swamp temperature was approximately 30˚C, with a variation range from 23 to 38˚C, and average *peten* temperature was 26˚C with a variation range from 21.5 to 32˚C (SMAD/CDB 1996).

In their literature review of mangrove response to salinity fluctuations, sedimentation and long-term flooding, Odum and Johannes (1975, 52-62) comment that radicular gas exchange is the mangrove forest's "Achilles heel". Siltation interferes with both the forest's nutrient cycling, and gas exchange between the rhizosphere and the water column or atmosphere (Lugo et al 1981, 129-153). It is to be expected that any increase in stressor intensity, whether that be roots' respiratory demands or blockage of the gas exchange involved in root respiration, should have a significant effect on trees' ability to concentrate and transport fresh water and nutrients to their leaves. This may lead to a progressive increase in leaf-fall and eventual defoliation if the condition is chronic. Under normal conditions, mangrove leaf production and loss is seasonal; leaves fall and are produced faster during the rainy season than during dry periods (Pool et al 1975). Lugo and Snedaker (1974, 39-64) suggest that excessive drought may lead to an abnormal leaf-fall pulse, essentially thinning the canopy, as leaf growth is almost non-existent during such conditions. Excessive leaf-fall results in a decrease in the system's photosynthesis capacity, and can lead to eventual ecosystem collapse if the stressor's effect is chronic or prolonged.

Other mangrove stressors discussed in the literature include hypersalinity (Cintrón et al 1978), high and low rates of water flushing (Hicks and Burns 1975), the effects of sand deposition on the forest soil (Cintrón and Pool 1976), and road construction (Patterson-Zucca 1982, 105-124). Roads cut superficial water flow in flooded coastal basins, mainly in the low swamp, the consequent water stagnation altering gas exchange between roots and sediments, causing toxin and salt incrementation, and favoring sedimentation (Snedaker and Getter 1985). Humans may tilt the balance in favor of higher mangrove mortality rates by introducing chronic stressors that inhibit regeneration mechanisms, as occurs in mangrove stressed by high salinity or alterations in drainage patterns (Lugo and Patterson-Zucca 1977, 149-161). These responses involve additive effects among stressors that accelerate energy losses and rapidly reduce a system's capacity to negotiate more stress.

The idea that stressors have the effect of reducing species diversity by increasing adaptation costs is likely accurate, because a stressor, by imposing energy barriers on a system, decreases its ability to support complexity. Theoretically, lower stress should increase an environment's carrying capacity. This occurs in high salinity environments after a storm decrease salinity stress, at which time species diversity increases for a short period, later decreasing to its original value as stressful conditions return to their original, high intensity. In the study area, a homologous situation occurred after hurricane Gilbert. Breaches in the coastal sandbar resulted in a strong increase in marine species in the swamp, these new conditions in turn causing a biological growing. This only temporarily benefited the local coastal fishery as it soon decreased.

In Florida, Cintrón et al (1978) recorded a maximum mangrove salinity tolerance, especially for red mangrove (*Rhizophora mangle*), of approximately 60-65 ppt, with germination ceasing above 65 ppt. They observed mean soil salinities of 44 ppt for live tree zones, 72 ppt for dead tree zones, and 87 ppt for salt flats. Red mangrove was reported as growing in salinities of up to 70 ppt, though optimal soil salinity for this species is 50–55 ppt. Tree height was inversely proportional to soil salinity, which measures from 17 to 72 ppt, with trees reaching up to 15 m in height in low salinity areas. When soil salinities exceeded 65 ppt, dead tree basal area was greater than live tree basal area. Carter et al (1973) suggest that trees in high salinity environments tend to transpire less than in low salinity conditions, thus at very high salinities one would expect a decrease in mangrove net productivity.

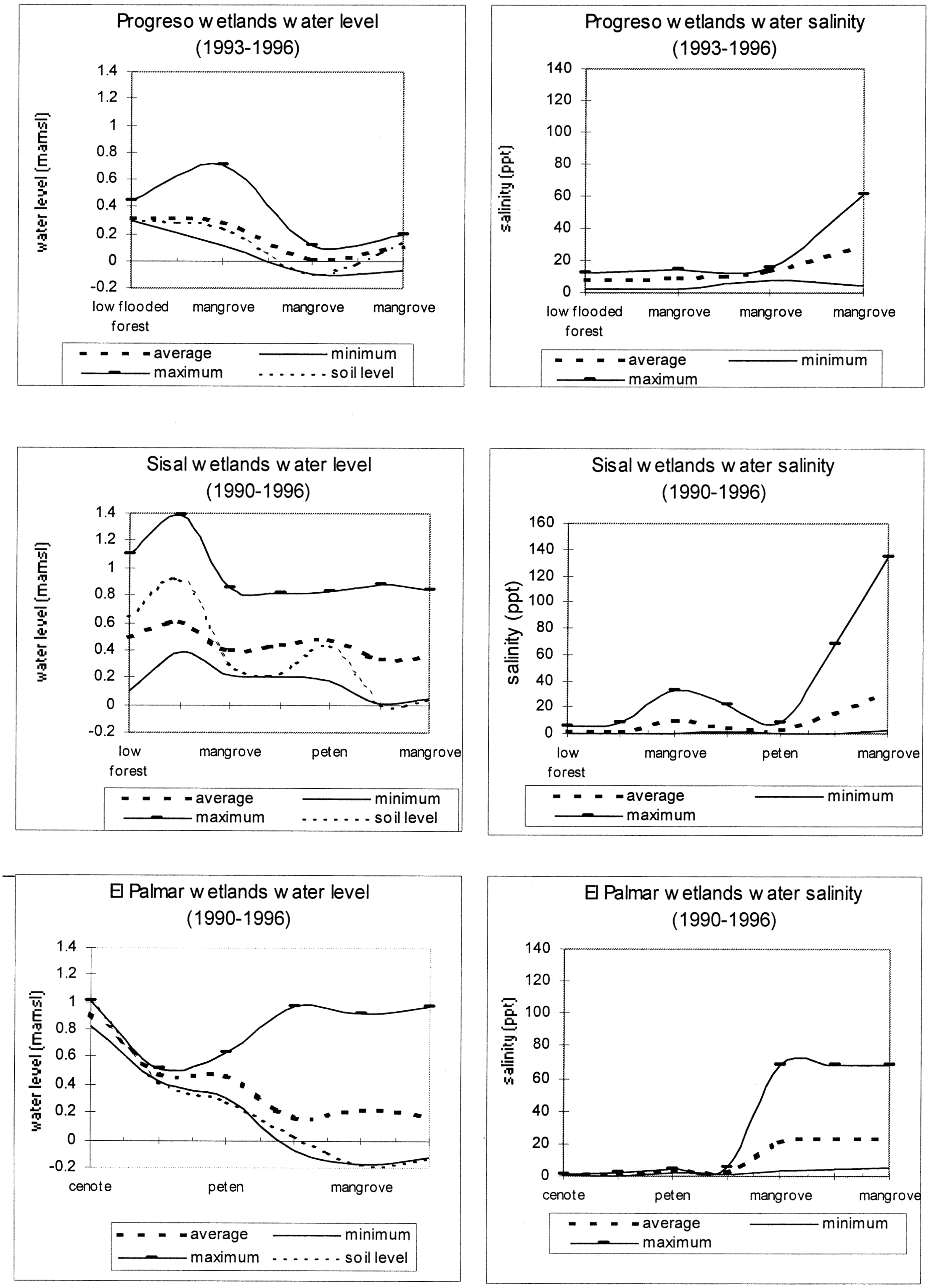
Valdés et al (1994, 61-75) studied water salinity in the Progreso-Chelém lagoon documenting the existence of three regions: the east zone, with large salinity variations (10-71 ppt) due to natural factors (rain, springs, evaporation), and human alterations (domestic and industrial water pollution, and lagoon areas isolated by roads, highways, and railroads); the central zone, with stable salinity conditions (23-42 ppt), due to the great dynamic exchange through the Port of Yucalpeten entrance; and the western zone that crosses the lagoon to Chuburná, a generally hypersaline zone (71 ppt) due to its isolation from the rest of the lagoon.

Salinity in the study area has been reported as increasing westwardly (SMAD/CDB 1996), with dry season levels at ca. 60 ppt in Progreso, 70 ppt at El Palmar Reserve and 140 ppt near Sisal. This increase is caused by incoming sea water, high evaporation, and wind-driven water movements. The lowest observed water level, in reference to mean sea level, was recorded during an extremely dry season in March 1995, and the highest level (recorded at Sisal and El Palmar Reserve) during extreme flooding associated with hurricanes Opal and Roxanne in October 1995. There is an inverse relation between water level and salinity during both the dry season and strong flooding periods such as the northwind season and hurricanes (Figure 6).

The deposition produced and discharges received during hurricanes and tropical storms have opened breaches in the coastal sandbar, mainly in fragile areas. As mentioned previously, the principal changes to coastal morphology after the 1988 Hurricane Gilbert were due to the opening of 12 breaches between the swamp and the sea on the northwest coastal zone of Yucatan. Three breaches were present in the study area: El Palmar, La Carbonera, and Chuburná. After the closing of the El Palmar breach the average wetland water level rose slightly. However, water level variability compared to average water level increased considerably after the closing, with water level ranging from 0.2 m before the closing to 0.44 m after, and maximum flood level ranging from 0.08 mamsl (meters above mean sea level) before to 0.33 mamsl after. Also of note is that average salinity decreased by half from 46.8 ppt before to 27.3 ppt after. The maximum recorded salinity value remained similar before and after the closing (54.8 to 57 ppt, respectively), though the minimum value decreased drastically from 37 ppt before to only 5 ppt after. There were also notable changes in the hypersalinity period. Before the closing the hypersalinity period, that with more than 40 ppt, lasted 6 months, from April to September 1990. During these months the soil was always flooded with at least a thin layer of water in the swamp mangrove. After the breach closing in 1991, the hypersalinity period was reduced to the two months of June and July, with a period during which the soil dried and cracked. These changes are an indicator of how marine processes can dominate low swamp processes, changing vegetation types over time. Just this as has occurred in Chuburná and Yucalpeten, where large salt flats now exist (Batllori 1995).

Seyle (1956) suggests that most environmental situations can become stressful to given individuals and that stress is a normal environment condition. The realization that stressors and energy drains are part of any natural environment is an important step in generalizing about stressors and their impact on ecosystems. Thus, it is very important to differen-

Figure 6.- Water level and salinity in Yucatan's northwest coastal wetlands between 1990 and 1996 (Source: SMAD/CDB,1996).



tiate between normal stress and additional stress caused by allogenic forces. The capacity of a system to regenerate depends on the availability of enough energy sources to reorganize it's disordered structure. Since the availability of energy is a function of environment, the type of environment dictates recovery rates and degree of complexity in steady-state (Lugo 1980, 65-72).

Mortality and expansion of mangrove forest in response to cyclic climatic events appears to be a common feature on arid coastlines. This association has at least two implications for mangrove management. First, managers should consider open water areas and salt flats part of the mangrove ecosystem and not as separate ecosystems. Failure to recognize this results in incompatible land uses that may affect the normal mangrove forest expansion during periods of high rainfall and lower soil salinities. Second, periods of high mangrove mortality are normal occurrences in these environments, and care should be taken before attributing this mortality to other factors, including human activities (Jiménez et al 1985, 177–185).

In general, catastrophic die-offs can be interpreted as the result of brief but extremely stressful episodes typical of many mangrove areas. Thus, massive die-offs are not "catastrophic" as mangroves are able to cope with these conditions. The real catastrophes occur when human misunderstanding of these systems functioning permits irreversible environmental changes from which no recovery is possible (Jiménez et al 1985, 177-185).

Conclusion

We conclude from our work that the coastal ecosystem is a stationary system subject to different natural environmental factors, including: a) soil hypersalinity and fresh water availability, which effect transpiration and photosynthetic capacity; b) sedimentation, which reduces nutrient and dissolved gas interchange between roots, soil, water and/or atmosphere.

Second, cyclic events associated with dry and wet years, as well as the recurrent presence of hurricanes, regulate the mangrove dynamic. In the present study area the 29-year drought between 1953 and 1982, and the 7–10 year hurricane period, are accompanied by hypersaline conditions, and low fresh water and nutrient availability, from which is to be expected a loss of natural vegetation and increase in salt flats. The system can adapt itself in order to survive since these stressors regulate growth rates, produce periodic set-backs in succession, are responsible for "young" ecosystem characteristics, and for the number of species able to survive in the system. However, it is precisely during periods of natural stress that human activities add non-selective, intense, unpredictable stressors to the system, such as canalizations for water, exportation of organic matter, and excessive sedimentation.

Third, during the previously mentioned period is when the greatest anthropogenic impacts began: a) Principal among these is the modification of the hydrological regime through permanent connection of the sea with the swamp, which results in the dominance of tidal flows in a new coastal morphology with large canals that export organic material to the littoral zone, sedimentation patterns that modify the substrate, and an increase in salinity; b) of continuing importance is the permanent obstruction of the parallel flow of water masses by coastal road construction, which principally effects the low swamp mangrove; c) dredging and filling of the swamp for harbor and living areas promotes sedimentation and loss of springs; and d) massive population migration towards the coast, with new settlement on unhealthy, trash fill along the swamp margin.

Aerial photograph analysis for the 1948-1979 period showed the greatest vegetation changes fundamentally in *peten* and scrub mangrove zones, with an annual loss of 1.41 km^2. In these areas, hypersalinization and sedimentation promote savanna vegetation to a great degree, and salt flats to a lesser degree.

After 1982, a rainy period began which continues to the present. Among this period's principal catastrophic events has been the 1988 Hurricane Gilbert, which opened various breaches such as those at El Palmar, Chuburná and Carbonera, the latter one remaining open to date. Even though it is hoped that these high precipitation conditions will be favorable for the ecosystem, those anthropogenic stressors mentioned above in #3 have caused residual and chronic effects. These effects can be seen in that the new vegetation structures that have developed exhibit little vigor and a low energy maintenance capacity, which inhibits their regeneration. If these chronic anthropogenic stressors, fundamentally the permanent communications with the sea and coastal roads, had been mitigated in the past decade mangrove recuperation would be much more vigorous, and the accelerated loss of low flooded forest would not be on the threshold of being considered an irreversible process.

In the 1979-1991 photographs, it was observed that though the *peten* and scrub mangrove zones show strong annual losses, the greatest change has been in the low basin mangrove, where extensive salt flats have been forming at a rate of 1.66 km^2 annually. This is a result of permanent change in the hydrological regime, marine sediment introduction, loss of springs, hypersalinity and erosion, which are promoting the accelerated transformation of low flooded forest into forest with savanna at a rate of 1.41 km^2 annually.

Finally, it is recommended that the State Government continue restoration activities in an effort to reduce the effects of chronic ecosystem stressors and increase energy retention capacity during this rainy period to allow for regeneration of the system. This work should develop a success index monitoring system, such as surficial and intersticial water salinity; mangrove growth; and mangrove community structure, to evaluate the rehabilitation activities. The characteristic vegetation in this area is mangrove classified as shrub type, which exhibits low structural development, indicating that it has been strongly impacted, analysis of changes in mangrove development will permit an estimation of the restoration success.

Endnote

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