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Cover photograph – "Little Ricky" - juvenile dolphin, San Salvador, Bahamas (courtesy of Sandra Voegeli, 2003)

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ECOLOGICAL EFFECTS OF SEA-LEVEL RISE ON MANGROVE AND FRINGING UPLAND VEGETATION AROUND BLUE HOLE PONDS ON SAN SALVADOR ISLAND, THE BAHAMAS

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ABSTRACT

Global climate change and the corresponding rapid rise of sea-level in recent decades are causing widespread changes in coastal wetland vegetation. The current rate of eustatic sea-level rise, 2-3 mm/year, may be obliterating some inter-tidal species and communities. Tropical mangrove communities and fringing upland vegetation are especially at risk.

San Salvador's mangrove communities include red mangrove (*Rhizophora mangle* L.), black mangrove (*Avicennia germinans* (L.) L., white mangrove (*Laguncularia racemosa* (L.) Gaertn.f., and buttonwood (*Conocarpus erecta* L.). These species vary in their adaptations to high salinity, low nutrient and oxygen availability, salt spray, and tidal inundation. Our earlier studies suggested that the "normal" mangrove zonation is changing, and so we sampled blue hole ponds in the northeastern corner of the island to determine possible causes of this unusual situation. We established transects at the six major ponds behind the Gerace Field Station. On each transect, tree species, number, and basal areas near the ground were measured. The elevation of each sampling point was tied to benchmarks adjusted for 1994 MSL, which was 18 cm higher than the 1929 National Geodetic Vertical Datum (NGVD).

Our data support the hypothesis that recent sea-level rise is having a deleterious effect on white mangroves and buttonwood, and to some extent, on black mangroves. Of these, trees with the largest basal areas were found at or near the water's edge, an environment in which they could not have started growth. Also, most of the dead trees in the study area were black or white mangroves, as determined by analysis of xylem cells. Where there is no suitable higher ground to colonize, these species are disappearing.

Red mangroves, however, will spread inland wherever daily tides can reach, displacing the other mangrove species and eventually the lowest upland vegetation. Thus, diversity of mangrove communities will decrease as sea-level continues to rise.

INTRODUCTION

Recent Sea-level Studies and Coastal Vegetation

Global climate change and the corresponding rapid rate of sea-level rise may be linked to widespread changes in coastal vegetation. Recent studies have shown that the current rate of sea-level rise (1-2.5 mm/yr) may be too fast for certain coastal wetland species to survive (Barnett 1984, Warren and Niering 1993, Gornitz 1995, Gutenspergen *et al.* 1997, Stumpf and Haines 1998).

Ellison and Stoddart (1991) reviewed the stratigraphic record of mangrove vegetation during sea-level changes of the early Holocene, and concluded that mangroves on low islands could keep up with a gradual rise of 0.8 – 0.9 mm/yr, but not with changes of 1.2 mm/yr or higher. Similar work by Parkinson *et al.* (1994) on early Holocene sea-level changes of the wider Caribbean region predicts submergence and disappearance of mangrove communities if sea-level rise reaches 3.5 – 4.1 mm/yr.

Exceptions to the classical zonation pattern of New World mangroves described by Davis (1940) and Chapman (1975) have been noted for San Salvador Island by Kass and Stephens (1990), and Godfrey, P. J., *et al.* (1993), and confirmed by this study. Rather than the expected sequence of red mangroves in tide water, bordered landward by black mangroves in soft high tide muck, then white mangroves above the normal high tide, and, finally, buttonwoods in the storm tide zone or on sea scarps exposed to salt spray, we found no predictable zonation.

Red mangroves do grow in salt water, and also to the edge of the upland forest as well. Large diameter black mangroves stand in or near salt water, but most are dead or dying. Buttonwood shrubs and trees occur though out, mainly at upper levels, while those near salt water are severely stressed. We wanted to find out why.

Sea-level Data

Figure 1 shows a list of various sea-level studies over the past 20 years, based variously on geological analyses, tide-gauge data, and changes in biological zonation. All confirm that the rate of rise has increased substantially during the latter half of the 20th century to at least 2 mm/yr, and is likely to continue increasing during the foreseeable future, placing all present-day coastal environments (natural and man-made) in serious jeopardy.

SUMMARY OF SEA LEVEL RISE DATA and SOURCES

- **GEOLOGICAL: Isotope (strontium) ratios.**
- **Sangamon–Age strata** (120-130 kybp (Curran, A. & B. White)
- **Wisconsin cycle: C14**
  - Holocene(15 kybp – 4 kybp = 2.2 mm/yr (Redfield, Emery, Garrison, etc.)
  - Modern (4 kybp – 1900s) = 0.4-1.0 mm/yr (Boardman, etc.)
- **TIDE GAUGES** (Hicks, S.)
  - Global (1880 - 1980) = 1.1 mm/yr..
  - Florida (1910 - 1970) = 2.0 mm/yr
  - New England (1940 – 1975) = 2.5 mm/yr
  - New Jersey (1940 – 1975) = 4.5 mm/yr
  - Bermuda (1880 – 1980) = 2.6 mm/yr
- **MARINE ANIMALS AND VEGETATION**
  - Florida oysters and barnacles = 4.7 mm/yr
  - N.J. & S.C. salt marshes = 2.6 mm/yr
  - San Salvador Island = 2.4 – 1.8 mm/yr (Davis, L., P. Godfrey, & Judy Wells)
- ***AVERAGE*** = 2.8 mm/yr
- **SATTELITE AND OTHER RECENT PHYSICAL MEASUREMENTS**
  - World-wide estimate = 2.0 mm/yr (Compare to Holocene rate)

Figure 1. Changes in sea-level over the past century (data from various sources).

Figure 2 shows the generally accepted sea-level curve for the past 10,000 years in the Bahamas (Boardman, M. R., *et al.* 1989). The rate of rise was about 2 mm/yr in the early Holocene, and then began slowing to about 0.1 mm/yr for several thousand years until modern times. Note that the modern rate equals that of the early Holocene. It is widely accepted that changes in the sea-level curve during the past century are the result of global warming instigated by the Industrial Revolution, and continually increasing quantities of greenhouse gases being released by modern society, a trend likely to get much worse in the 21st century.

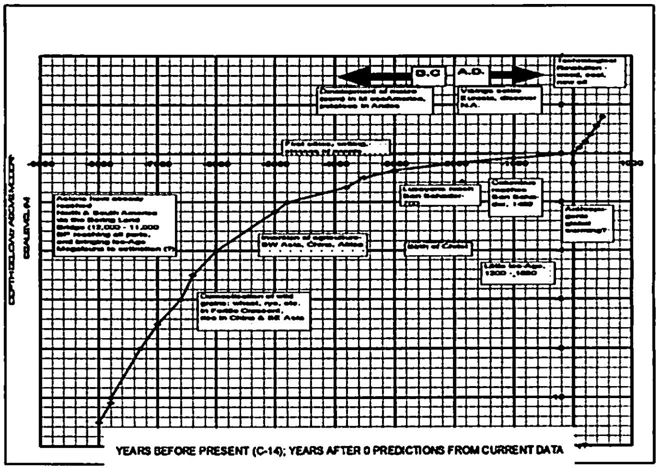


Figure 2. Bahamas sea-level curve from Boardman 1989. (The graph has been annotated to show events in human history as sea-level rose to current levels.)

OBSERVATIONS AND HYPOTHESIS

Study Sites

San Salvador Island is located 611.5 km (380 miles) east-southeast of Miami, Florida, at the southeastern end of the Bahamian Island chain at 24° 00' N and 74° 30' W. The island consists entirely of limestone with maximum elevations of about 30 m (100 ft) on ancient lithified dunes, although most of the land is low, contains shallow, saline lakes, ponds, swamps, barren flats, etc., which are relatively close to sea-level making the island suitable for studying the eustatic effects of oceanic changes over recent millennia. San Salvador Island has been isostatically stable during the Holocene, forming with the Bahamian Bank and moving westward as the Atlantic Ocean opened (Sealy 1985). San Salvador Island stands alone at the eastern edge of the Bahamian Archipelago, and was the first landfall of Columbus in 1492.

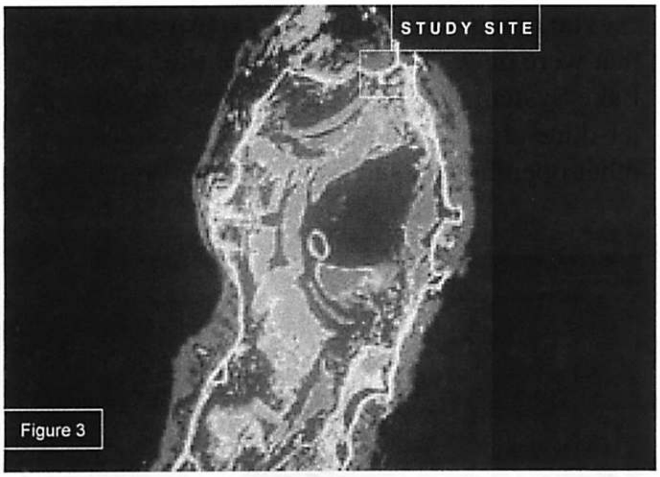


Figure 3. San Salvador Island with location of study site. (KEY: light gray=central hypersaline lakes; dark gray=wooded uplands on old dunes; very light gray (lower right)=normal lagoon; white=shoreline; shades of gray offshore=coral reefs and sand flats; darkest gray in center=clear lake with surrounding beach; black=deep ocean.
(Satellite photo courtesy of NASA; ground truth by Clark, C. A., *et al.* 1992.)

The island is about 19.3 km (12 miles) long and 9.7 km (6 miles) wide with a more-or-less rectangular shape. The central region is dominated by extensive hyper-saline lakes (noted by Columbus) which are dominated by a diversity of microbes. The high salinity in these lakes (2 to 3 times that of seawater) is caused by low rainfall and high evaporation as tide water rises to the surface from below and becomes trapped with no overland drainage back to the ocean. Only true blue-hole ponds, with direct tidal "pipelines" through the sponge-like limestone below, have ocean salinities, clear water, and rich, unique, marine ecosystems.

The uplands consist of lithified Pleistocene dunes located in the center and around the island's periphery, covered by sub-tropical/tropical coastal scrub woodland. Countless depressions, holes, and caves (some now containing tide water) puncture the upland surface everywhere (Figure 4a).

Modern coastal dunes are located mainly along the eastern shore, and are high, stable, and covered with a rich strand vegetation. These dunes, and the interior uplands as well, have been used for subsistence gardening since the 1700's by descendents of slaves. The island is ringed by a newly paved road connecting several villages, a new airport, Club Med, and other sites proposed for development, ALL of which will be affected by sea-level rise in the near future.

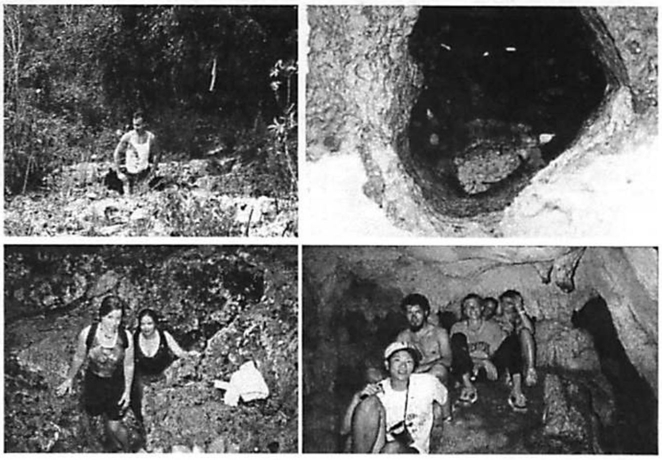


Figure 4a. The island surface is pitted with countless solution holes affected by daily tides (top row); Lighthouse Cave partially fills with diurnal tide cycles, but still has enough room to be explored by visitors, in or above the water (below).

Many changes occurred on the island during the 130,000 years preceding the Wisconsin Glaciation. The ancient column of limestone we now call San Salvador Island stands alone on the sea bottom detached from the Bahamian Bank. The whole region was submerged during the Sangamon Interglacial by 2 or more meters of seawater, and marine environments covered San Salvador, as shown by Sangamon-age oceanic and lagoon deposits found there today.

When the Wisconsin Ice Age began, the developing glaciers derived water from the sea, and its levels dropped, exposing the former marine environments to the atmosphere. These communities died, and the resulting carbonate sand was blown into large dunes in the center and around the periphery of the island by strong northerly glacial winds. Over time the dunes lithified into limestone, including aragonite. The winds blew carbonate sand all the way from the surface down to stone, including aragonite. The winds blew carbonate sand all the way from the surface down to

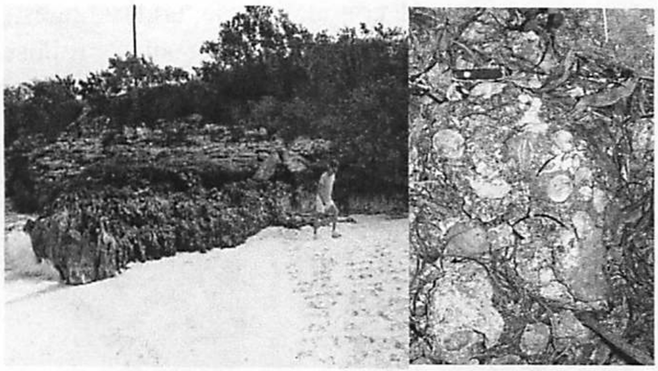


Figure 4b. Biological evidence of sea-level change over the last 130,000 years on San Salvador: Sangamon-age coral reef at Grotto Beach. (left), and fossil Codakia orbicularis shells and other marine lagoonal sediments near Pain Pond.

Sangamon facies, where lag-layers of shells and oolites had cemented into the rock we see today. The surface was, and still is, well-vegetated, except where rocks are exposed in the driest and most severe locations.

At the same time, tropical and subtropical plants began colonizing the now exposed land as air-and-water borne propagules reached the island from the large Caribbean Islands to the south, and the nearby exposed Bahama Bank. Over the tens of thousands of years of exposure to air, the islands became covered by plant communities of many types, and the land acquired its most diverse flora since previous glaciation cycles.

The island was deluged with rain throughout the 100,000+ years of exposure, and fresh water dissolved away vast quantities of limestone, creating sink-holes, caves, tunnels, and chambers throughout the island. Water running down into the island exited at various sea-levels, and at different times, that can be seen by divers venturing down the island's submerged "Wall". Openings that permeate a limestone structure can only do so when it is not submerged in water.

Once the Wisconsin ice sheets began to melt, sea-level rose rapidly around the island at about 2-4 mm/yr, filling all the open caves, tunnels, and chambers with seawater. This process had no effect on surface vegetation until salt water began reaching the surface.

The rising sea has already destroyed forests that were once in the large hyper-saline Great Lake System (Figure 5), and is now flooding inter-dune regions, all of which have conduits, or other openings, to salt water below (Figure 6).

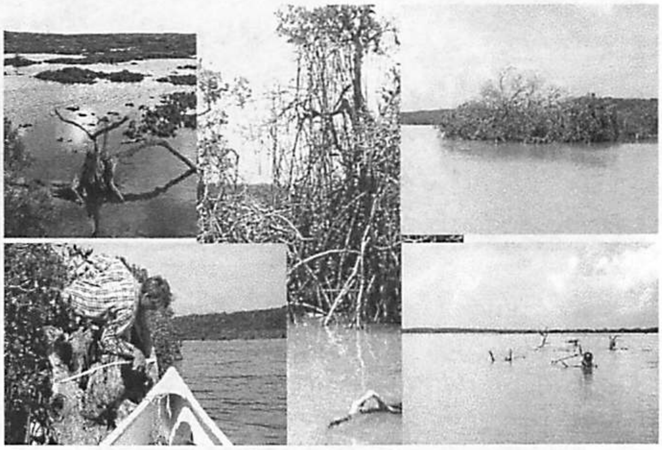


Figure 5. Dead and dying trees in the hyper-saline lakes. A graduate student with a 1 m diameter unknown species (lower left).

Figure 6. Pleistocene dunes with salt water in low areas between (above), and the upper edge of the interior lake system (below).

This project was conducted in four inter-tidal ponds south of the Gerace Field Station on the northeastern tip of San Salvador (Figure 7). Two of these are inter-dune ponds, while the others are in the low elevation Sangamon facies south of the dunes. Normal tidal cycles and precipitation affect the water levels in all the ponds, but the smaller are affected only by tides, not wind or waves, as in most other coastal areas. These tidal holes provide excellent sites to study sea-level rise because they serve as effective "stilling wells" (Figure 4a: upper right.) As sea-water gets higher and higher, it only affects the plants that surround the hole and nearby vicinity. During extra high tides, sea water actually flows down from some of these holes into the nearby lakes and ponds (particularly at Osprey Lake).

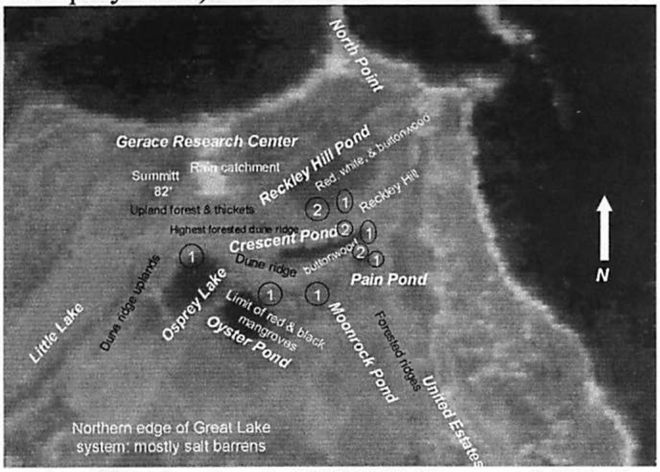


Figure 7. LANDSAT image of NE San Salvador, showing the blue hole pond mangrove study area.

METHODS

Two sites were sampled at Reckley Hill, Crescent, Pain and Moonrock Ponds shown in Figure 7, as well as on a long transect across limestone flats at Oyster Pond. The sites were chosen at random in those swamps where a person could actually enter the vegetation. At each site a baseline was run approximately parallel to shore. Five randomly selected transects, each 5 m long, were laid out perpendicularly to the baseline and divided into five 1 m^2 plots. In each plot, the tree species were recorded, tree numbers counted, and the trees' basal areas near the ground measured (Figure 8).

Elevations were measured at each pond with a surveyor's transit and tied into the previously established benchmarks relative to 1929 mean sea-level datum (Davis L., P. J. Godfrey and J. Wells 1994; Godfrey, P. J., *et al.* 1993).

Average basal areas for species in the plots were calculated and tested for significance using analysis of variance with *KEYSTAT*.

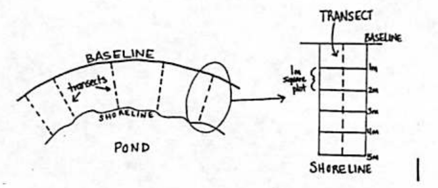


Figure 8. Sampling design for the mangrove study.

RESULTS

Vegetation Analyses and Elevations

Reckley Hill Pond. The two sites at Reckley Hill Pond contained three of the four mangrove species found on San Salvador: red mangroves, white mangroves, and buttonwoods. Red and white mangroves, both alive and dead, dominated Site 1 (Figures 9 and 10).

Basal areas of red mangroves ranged from 65.6 cm^2 to 474.6 cm^2, and were present in all plots, with the largest trees being closest to the upland. There was a significant difference along the transect ($p < 0.001$, $n = 319$).

The basal areas of live white mangroves were between 138 cm^2 to 263 cm^2, present in 4 plots, but not significantly different ($p > 0.05$, $n = 7$). Dead white mangroves showed the greatest range in basal areas from 34.2 cm^2 to 3,267.5 cm^2 with the largest trees 3 m into the pond, and smaller ones in the other two plots near the upland. The dead white mangrove plots were significantly different because of the large tree in the 3 m^2 plot (Figure 9 [right]).

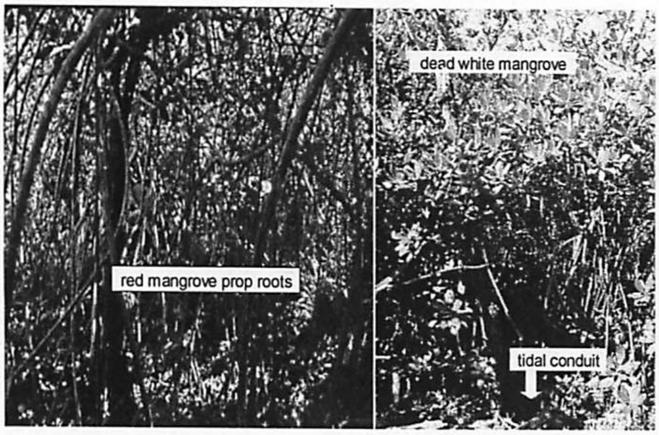


Figure 9. Reckley Hill Pond Site 1. Red mangrove transect (left) shows the tangle of prop roots and branches which had to be entered so only trunks could be measured. The main salt water tidal conduit (right) is surrounded by red mangroves, but with a dead white mangrove tree standing in seawater behind.

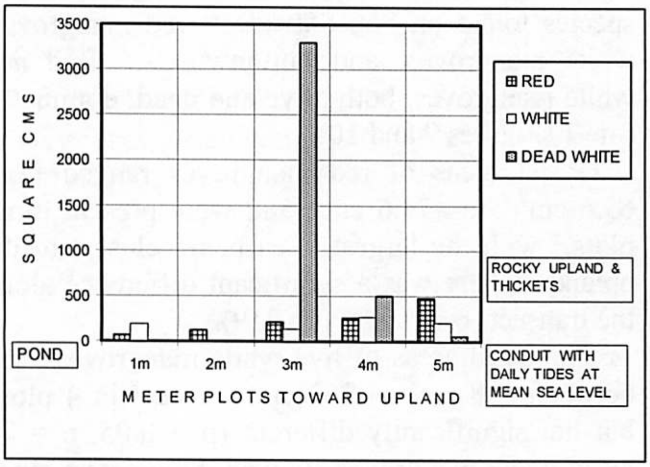


Figure 10. Reckley Hill Pond Site 1. Total Basal Areas (cm^2) for mangroves on transect.

Site 2 at Reckley Hill Pond (Figures 11a and 11b) had all three species of mangroves (Figures 11 and 12). Red mangroves were present in every plot with basal areas between 171.6 cm^2 and 385.2 cm^2, the largest at 3 m on the transect, and the means between plots significantly different ($p<.0.01$, $n = 292$) (Figure 12a).

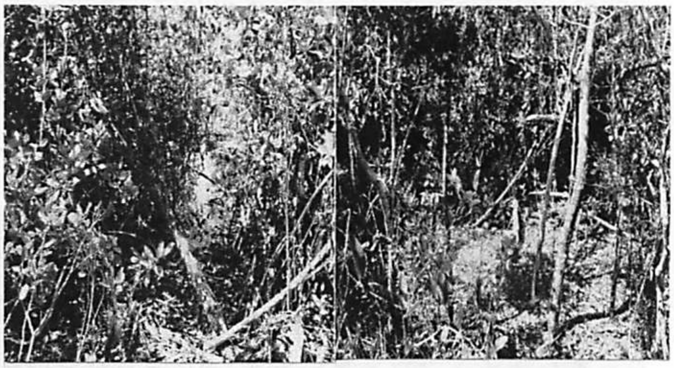
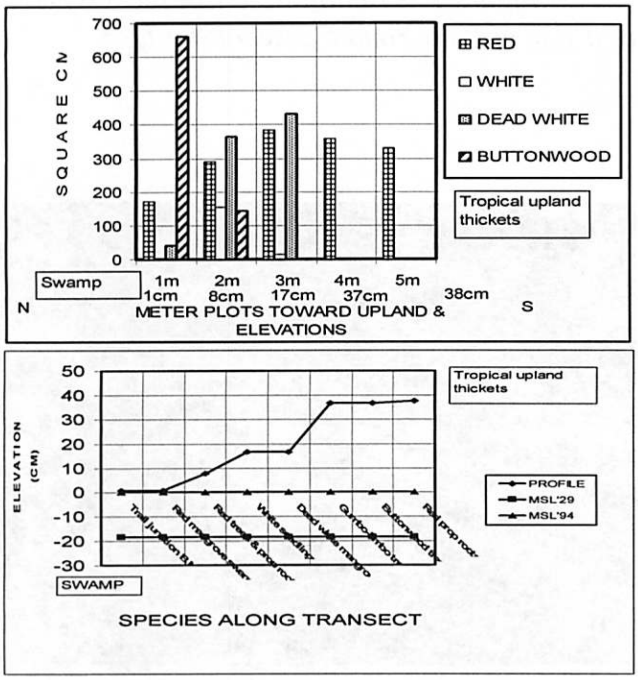


Figure 11a. Reckley Hill Pond Site 2: Transect down into the red mangrove swamp (left) containing a mixture of prop roots and salt water with white mangrove and buttonwood trunks in the foreground. A large dead white mangrove stands beyond the water. The surrounding upland area (right) contains buttonwood, white mangrove and gumbo limbo (Bursera simaruba), with red mangrove prop-roots climbing up the slope.

Figure 11b: Easterly trail around south side of Reckley Hill Pond. The trail once passed well to the left of the large, twisted buttonwood (with hat) on the left; the present trail on the right is higher, but wet nearly all the time. This tree could not have started growth in its present location. Inset on right (view to the west) shows the former trail being invaded by pond water and red mangroves. Buttonwood and white mangrove shrubs are dying. A new trail was made on uplands to the left.

Basal areas of live white mangroves were low and ranged from 13.2 cm^2 to 153.9 cm^2, but were not significantly different between plots ($p > 0.05$, $n = 2$). However, dead white mangroves were found in the three lowest transect plots with basal areas of 38.5 cm^2 to 431.6 cm^2, the largest at 3 m inland, but plot means were not statistically different ($p > .05$, $n = 6$).

Buttonwood was also present on a transect with the largest tree (660.5 cm^2) at the 1 meter plot next to the pond. The second buttonwood was smaller (143.1 cm^2) and in meter #2. The means were not significantly different since no other buttonwoods were found on the transect ($p > 0.05$, $n = 2$). The fact that buttonwoods, as well as white mangroves (living and dead), were there at all shows a major environmental change occurred since those species were seedlings. The total number of mangrove trees counted and measured at both sites was 632.



Figures 12a and 12 b. Reckley Hill Pond Site 2. Red mangroves grow in all plots up to the trail.

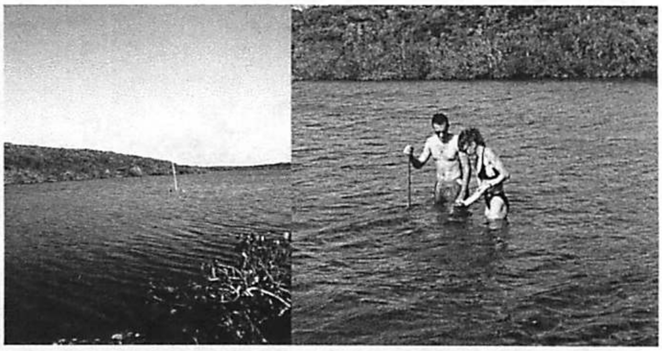


Figure 13. Crescent Pond: survey rod shows location of primary sea water conduit(left); students sampling organisms in shallow water, the most typical habitat in the pond(right).

Transects at all other ponds from Crescent to Moonrock contained only buttonwoods. These ponds are surrounded by lithified dunes, or high ground not yet breached by seawater floods which could carry the water-borne propagules of red, black and white mangroves across the intervening uplands. In contrast, buttonwood seeds are airborne and can spread throughout the area.

At Crescent Pond, Site 1 (Figures 14 and 15), basal areas of buttonwoods in 4 plots nearest the upland were small (25 cm^2 to 50 cm^2). However, a much larger tree (320 cm^2) was in the first quadrat by the pond and caused the positive statistical difference between the plots ($p < .05$). Elevations of buttonwoods went from +34 cm to +48 cm in contrast to those at the protected area of Reckley Hill Pond where they were closer to sea-level (Figure 12).

On the north side at Site 2 buttonwood basal areas were about the same as in Site 1 ranging from 50 cm^2 to 220 cm^2 in plots 2 to 4, but there were no significant differences ($p >. 05$) (Figure 16).

Figure 14. Buttonwood transect on the east side of Crescent Pond.

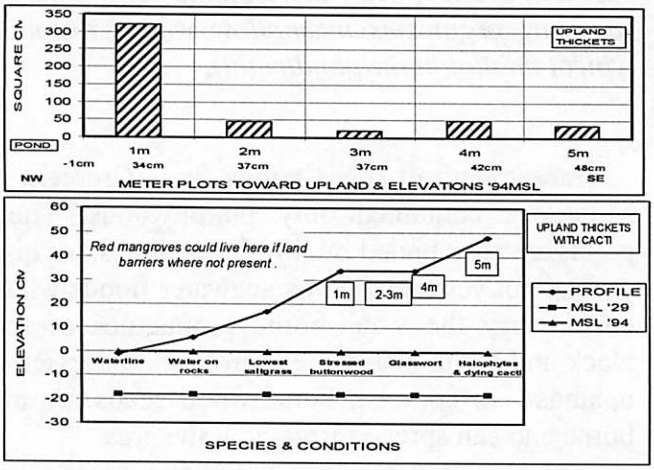


Figure 15. Total basal areas (cm²) of buttonwoods and elevation profile at Crescent Pond.

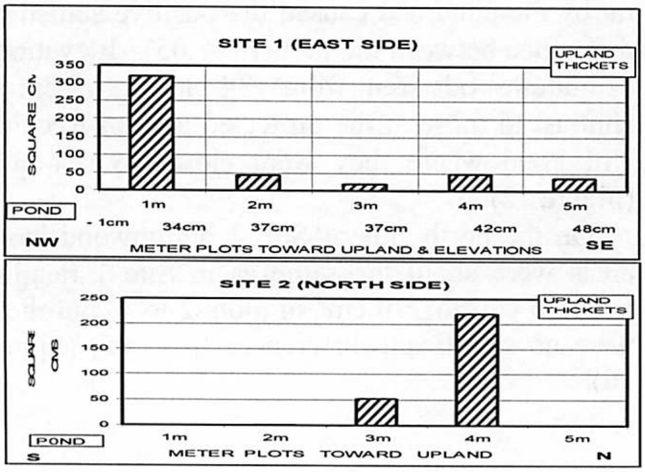


Figure 16. Comparison of buttonwood basal areas on north and east sides of Crescent Pond.

<u>Pain Pond</u> (Figures 17, 18, 19). The buttonwoods on both sampling sites were small in stature and severely stressed. These locations are subject to a great deal of salt spray and flooding during storms (Figures 20 and 21).

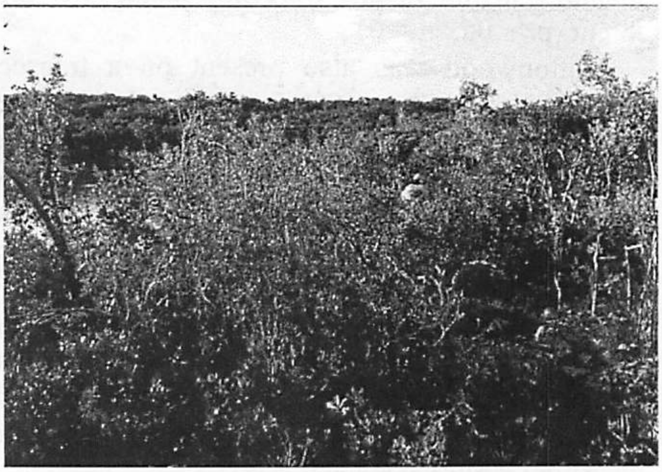


Figure 17. Buttonwood transect on the east side of Pain Pond transect (Site 1).

Figure 18 . Sampling stressed buttonwood vegetation on the north side of Pain Pond (Site 2).

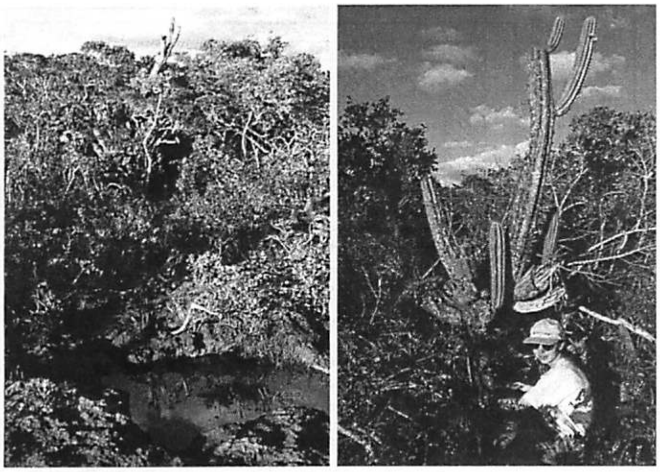


Figure 19. East side of Pain Pond with a large old man's beard cactus (Cephalocereus millspaughii) dying from salt water flooding.. Note seawater in a tide pool, lower left. A student (right) is measuring its diameter and distance from the tidal water.

The buttonwood data on Pain Pond transects were very similar to those at Crescent Pond (Figure 20). Trees were found in every plot from meter 1 toward the upland (shore). Basal areas were small ranging from 10 cm^2 to 62 cm^2 and showed no significant differences between plots at Sites 1 and 2. Following the Crescent Pond pattern, buttonwoods were well away from the water at elevations above 49 cm. The transect went up to elevation 70 cm where several specimens of old man's beard cactus were being affected by salt water (Figure 19).

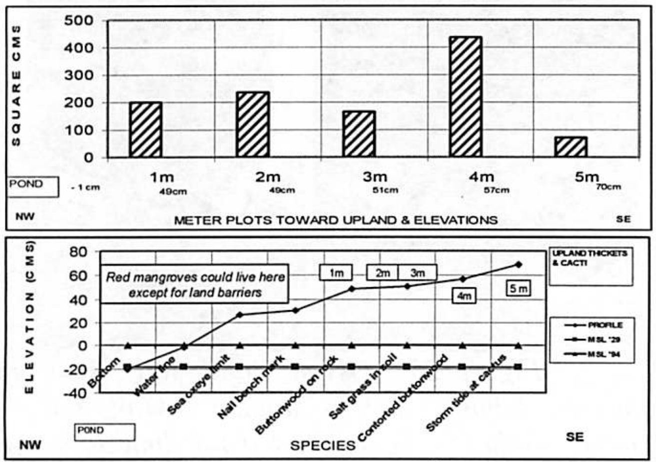


Figure 20. Total basal areas (cm^2) of buttonwoods along the transect and on profile at Site 1 of Pain Pond shore (meters coincide with plots).

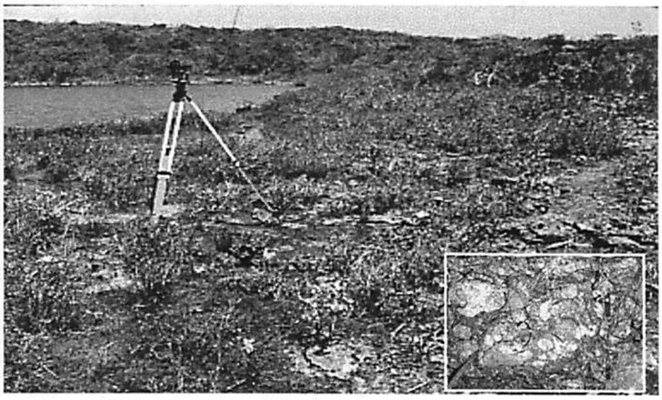


Figure 21. The western end of Pain Pond has a tidal salt marsh with stunted halophytic shrubs and grasses, but no mangroves. The site also contains the first Sangamon-age Codakia bivalves found in the pond area (inset).

Moonrock Pond (Figures 22, 23, and 24). The most severe shoreline environment we studied is around Moonrock Pond (named for its knife-sharp karst textures). It consists of highly weathered limestone at the surface, with countless holes to tidal water a short distance below. This rock is also part of the Sangamon-age fossil layer. Since there is little relief separating this pond from the huge salt lakes to the southwest, the shore is inundated with salt spray and flooding during storms. The buttonwoods present above the waterline are very stressed with small basal areas ranging from only 2 cm^2 to 8.5 cm^2 with no significant differences ($p > .05$) between the plots on north or east sides (Figure 24). (Only data from Site 2 [north side] are shown in the Figure 24).

The Moonrock shore is so severe that stressed buttonwoods started at +70 cm elevation and went inland. As with Crescent and Pain Ponds, Moonrock has a wide inter-tidal/storm tide zone, but no mangroves. This is an open habitat that may be filled with mangroves when sea level rises higher and flooding carries in founder species which are not far away at Oyster Pond to the west.

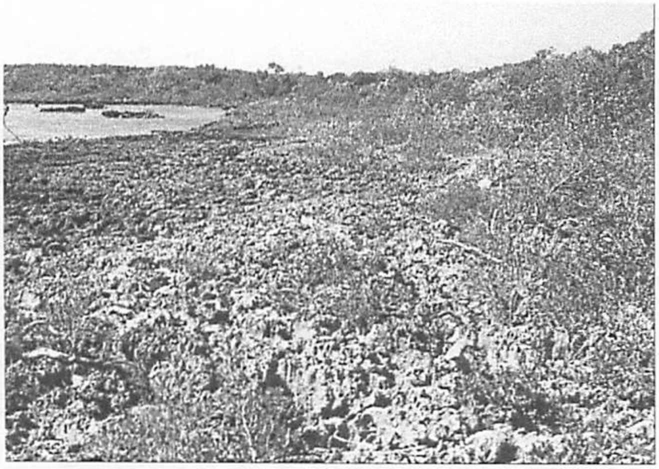


Figure 22. Moonrock Pond, east end, containing Sangamon fossils, and a vast number of openings to tide water just below the sharply eroded surface. Fossil Codakia shells are in the fore-ground rock, with scattered, stunted button-woods barely surviving on the surface, while halophytic plants grow in the salt water nearby.

Figure 23. Moonrock Pond: the inter-tidal north- western end, also containg fossil shells, tide holes, stunted shrubs, halophytes, and a salt water conduit, but no mangroves, as yet. (This has to be one of the worst island environ-ments for plants.)

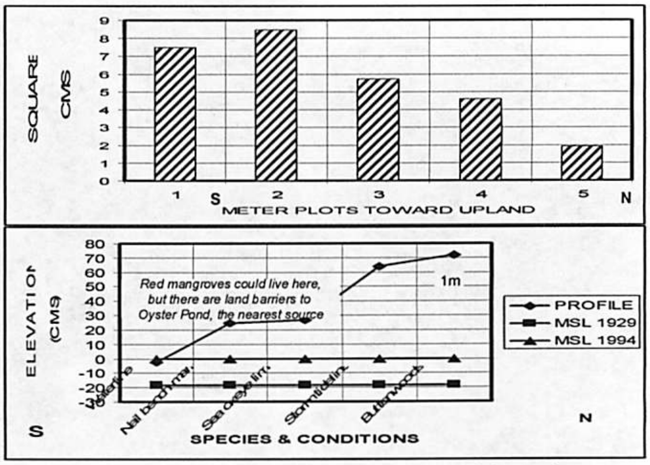


Figure 24. Total buttonwood basal areas (cm^2) on north side of Moonrock Pond (above), and the shoreline profile (below). Buttonwoods are at +70 cm in Plot #1.

Oyster Pond and surrounding flats (Figures 25 and 26). During January 2001, we measured the elevations of mangrove sites along a transect that began in an upland region containing species not associated with tidal habitats. These data are shown in Figure 26, and show the wide range of elevations occupied by the four mangrove species, some at expected, others not.

Elevations shown are corrected to 1929 MSL NGVD, based on sea-level rise measured in 1994 of +18 cm. The figure also shows the 1929 MSL line and indicates that all mangroves were well above sea-level then, but is not the case today.

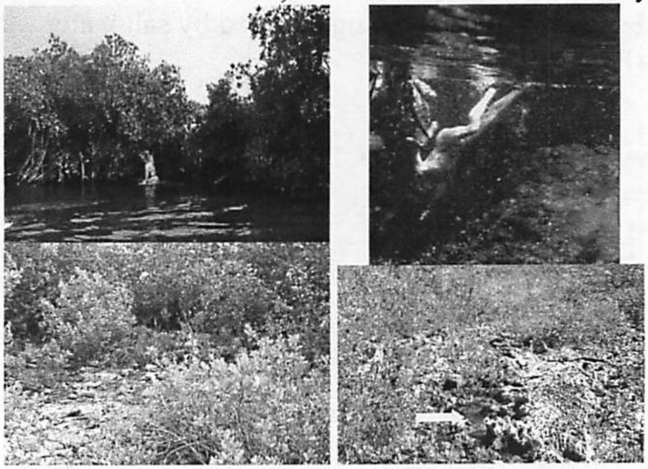


Figure 25. Osyter Pond: fully tidal and marine (above) with a student diving into the main conduit. Highly eroded flat limestone sur-roundings with fossil shells, and seawater flood-ing through holes in the surface (arrow, lower right).

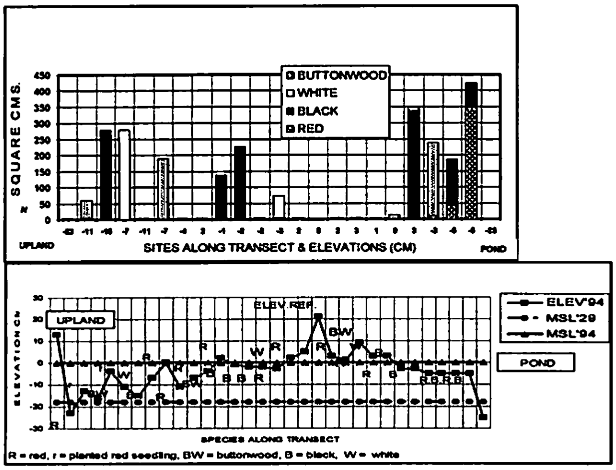


Figure 26. Total basal areas (cm^2) of four mangrove species at Osyter Pond and surroundings (above); elevations of mangroves on a transect to the pond (below).

The survey showed that species normally found well above MSL, such as white mangrove (WM), were -3 cm below sea-level near the pond. White mangrove trees found further from the pond's edge were near MSL (+2 to +3 cm), or below (-7 cm). The largest white mangroves were found in sites where they could not have started growing in recent years. These large trees were close to, or below, sea-level and showed signs of having been recently flooded (Figure 26).

Buttonwood (BW), a species that grows in uplands or fresh water swamps, was located near Oyster Pond at +9 cm and +2 cm above MSL, but was also found in tidal holes at -7 and -11 cm. If the 1929 MSL NGVD were used as the reference, these buttonwoods would be well above sea-level and in a more suitable zone. Data in Figure 26 show that the bases of the largest buttonwoods are now below sea-level. Buttonwood cannot grow near or below sea-level, so these trees must have started their lives when the sea was lower.

On the other hand, species generally found in the inter-tidal zone, such as red mangrove (RM) and black mangrove (BM), were best developed at the edge of Oyster Pond, which would be expected. The largest red and black mangroves were at -5 cm and created a thick ring of trees, about 10 m wide, encircling the pond.

The highest large black mangrove between the reference elevation and the pond was at 3 cm above MSL and healthy. Three other black mangroves were found on the mostly barren limestone flats around the north side of Oyster Pond, where innumerable erosion holes and pits exist, with sharp ridges between. One large black mangrove (with a basal area of 222 cm^2) was at -2 cm, while another tree close by (139 cm^2), was at -1 cm, both in solution holes. A third large black mangrove (278 cm^2) was at -15 cm in a deep hole. Black mangroves grow well at the upper levels of the tide zone, so it appears that these large, old trees began growth when sea-level was lower.

The only species benefiting from sea-level rise is red mangrove (RM), which is invading habitats occupied by other trees. Its propagules probably arrived at a time of lower sea-level several thousand years ago, but could not expand inland. At Osyter Pond red mangrove basal areas decrease dramatically away from the pond's edge (346 cm^2 and 44 cm^2 at -5.4 cm elevation, then down to 6 cm^2 and 4 cm^2 at +3 and +1 cm elevations). However, small red mangrove plants (4 +/- cm^2) were found throughout the transect in solution holes ranging from -3 to -23 cm deep. (Two red mangrove seedlings were planted in holes with elevations of -4 cm and -12 cm after the survey)

Tides rising up inside the island now flood these solution holes and allow young red mangroves to survive. In the past, tides could not flood these holes. Recent storm surges must have carried red mangrove seedlings across the "moonrock" and dropped some into holes and pits deep enough for them to start growing. In this way, red mangrove plants are migrating inland and will eventually dominate the region, while other species die off.

This pattern of "reverse succession" seen here is similar to the one we documented at Osprey Lake over 10 years ago (Godfrey, P. J., *et al.* 1994). The difference at Oyster Pond is the extensive limestone flats with countless solution pits and daily tide cycles where red mangroves can start growing. Red mangroves are also moving into fresh water swamps in Florida (Figure 27).

Figure 27. Dr. Don Gerace standing by a large, old, live oak tree (<u>Quercus virginiana</u>) next to a Southern Florida swamp. A red mangrove seedling (inset) growing at its base shows that high waters are reaching far inland sites where mangroves can now survive.

DISCUSSION

What can be done, if anything, to counter this major environmental change? The answer is: not much. The global warming trend is already underway. Oceans are increasing in volume by thermal expansion and additional melt water from glaciers in the Arctic and Antarctic. This cycle of rising and falling sea-levels has happened many times before (Figure 28).

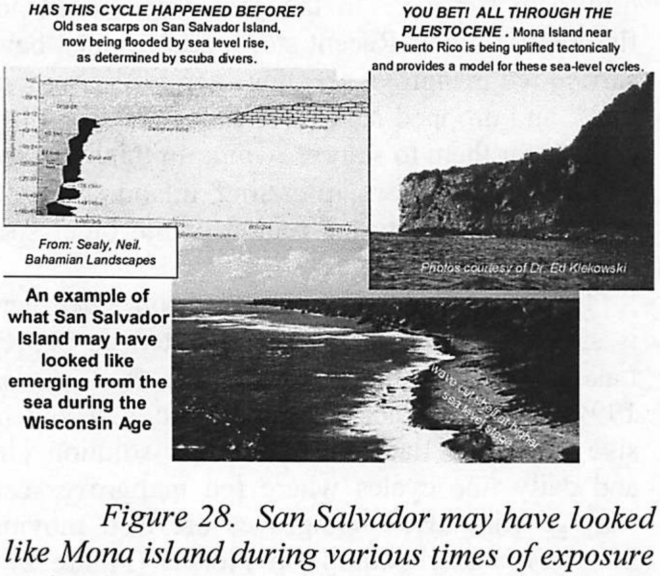


Figure 28. San Salvador may have looked like Mona island during various times of exposure and submergence during the Pleistocene times. (Photos courtesy of Dr. Ed Klekowski)

All man-made operations will have to move to higher ground. Any developments near swamps, and ocean shorelines as well, should be prohibited. Perhaps the least of the problems facing society is that all topographic maps will have to be corrected, although vertical measurements near sea-level will be most severely affected. Elevations shown on present-day maps were based on Mean Sea-Level of 0 NGVD in 1929. These elevations are now about 20 cm less than shown on today's maps, and the differences will increase substantially with each passing year as the ocean keeps rising.

We can, however, protect all the remaining mangrove habitats as much as possible. As sea-level rises, red mangroves will follow it to higher ground and provide barriers against wave erosion, a role to which they are well-adapted. Even if white and black mangroves die back, the red mangrove community will continue to provide important habitat for wildlife, fisheries, and a host of marine organisms (Figures 29 and 30).

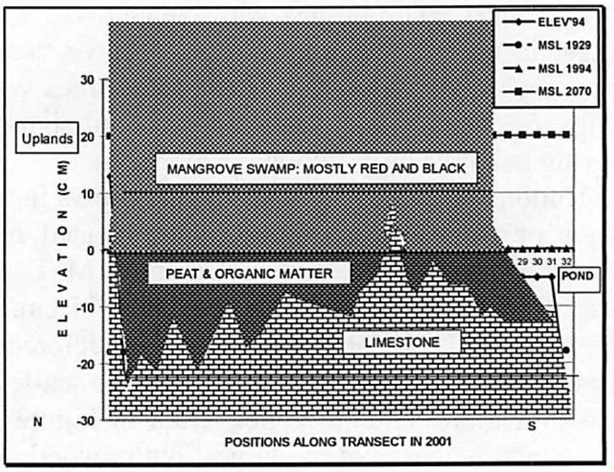


Figure 29. We predict that rising sea-level will cover the whole area surrounding Oyster Pond, and red mangroves will colonize present uplands by 2070.

Red mangrove seedlings can be planted on higher wet ground (saline or fresh) behind existing swamps, where they will serve as buffers when tides reach their new levels. We've tried this approach and found red mangroves transplant easily to salt or fresh water habitats.

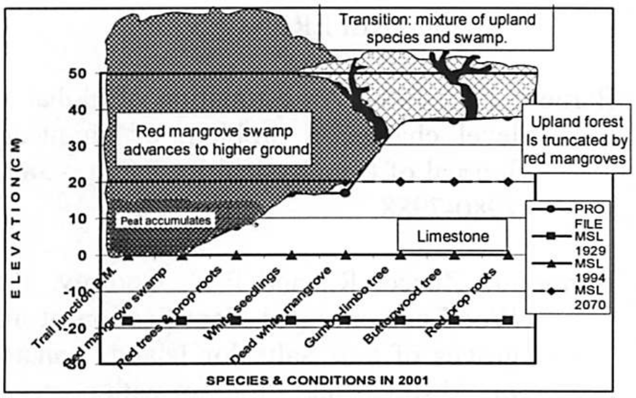


Figure 30. Predicted change of zones at Reckley Hill Pond due to sea-level rise by 2070.

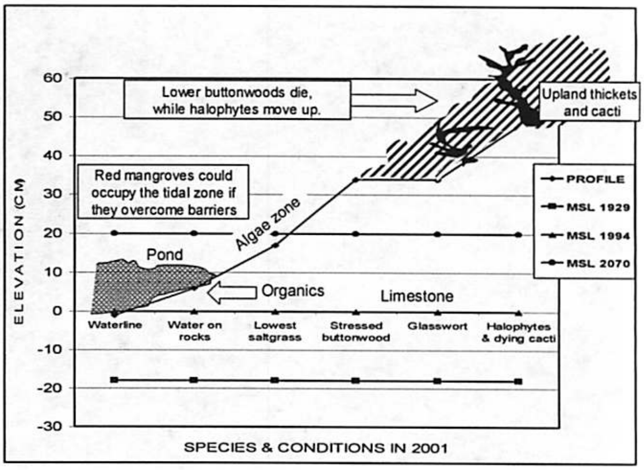


Figure 31. Predicted changes at Crescent Pond by 2070.

CONCLUSIONS

1. Our observations and data support the hypothesis that recent sea-level rise of about 2 mm/yr is having a deleterious effect on mangrove vegetation, particularly white and black mangroves surrounding blue-hole ponds and saline lakes on San Salvador Island.

2. Large, dead white mangroves were found standing in seawater near or slightly above MSL at sites where they could not have started growth, such as Reckley Hill Pond, Osyter Pond, and Osprey Lake. Such data alone show that sea-level has risen enough to kill these trees during their normal life spans.

3. Buttonwoods that have been growing near salt water are being killed or severely stressed, but those that are growing above the tidal zone can survive and spread further inland. However, typical upland vegetation, as exemplified by old man's beard cactus *(Chephalocereus millspaughii),* is dying as salt water invades its territory (Osbourne, H. 2001) (Figure 31).

4. Barton, J., *et al.* (1995) examined wood from dead trees flooded by high tides and found that they were primarily white mangroves and buttonwoods, with a smaller proportion of black mangroves. Layers of peat found below water level and out beyond existing vegetation in Osprey Lake contained stumps of black mangroves. This finding shows that black mangrove habitats were once more extensive here than today.

5. The spread of saline lakes has destroyed extensive areas of sub-tropical forest and scrub vegetation that had covered low ground for over 100,000 years in the interior regions of San Salvador.

6. If sea-level continues to rise, and there is nothing to suggest it will not, saline lakes will expand over the lower elevations, and red mangroves will spread inland wherever daily tides can reach. Ridges and uplands will prevent red mangroves from reaching some inland ponds. White and black mangroves, however, may be caught in unsuitable zones for their continued survival and establishment (Figure 32).

7. These rapid changes may cause white mangroves to disappear in the near future from locations where no remaining suitable higher ground exists, or they will become even more restricted than they are now. Thus, the plant diversity and extent of mangrove communities on San Salvador Island will decrease.

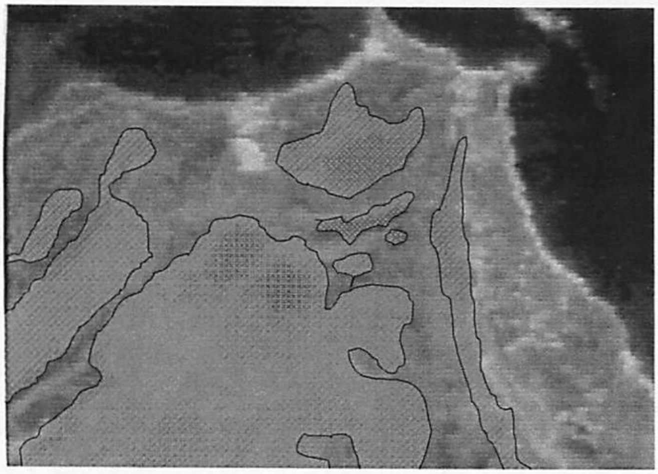


Figure 32. Possible expansion of saline ponds and lakes in NE San Salvador Island by 2070 at the current rate of sea-level rise.

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