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CUMULATIVE IMPACTS OF HURRICANES ON FLORIDA MANGROVE ECOSYSTEMS: SEDIMENT DEPOSITION, STORM SURGES AND VEGETATION

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Abstract: Hurricanes have shaped the structure of mangrove forests in the Everglades via wind damage, storm surges and sediment deposition. Immediate effects include changes to stem size-frequency distributions and to species relative abundance and density. Long-term impacts to mangroves are poorly understood at present. We examine impacts of Hurricane Wilma on mangroves and compare the results to findings from three previous storms (Labor Day, Donna, Andrew). Surges during Wilma destroyed ≈ 1,250 ha of mangroves and set back recovery that started following Andrew. Data from permanent plots affected by Andrew and Wilma showed no differences among species or between hurricanes for % stem mortality or % basal area lost. Hurricane damage was related to hydro-geomorphic type of forest. Basin mangroves suffered significantly more damage than riverine or island mangroves. The hurricane by forest type interaction was highly significant. Andrew did slightly more damage to island mangroves. Wilma did significantly more damage to basin forests. This is most likely a result of the larger and more spatially extensive storm surge produced by Wilma. Forest damage was not related to amount of sediment deposited. Analyses of reports from Donna and the Labor Day storm indicate that some sites have recovered following catastrophic disturbance. Other sites have been permanently converted into a different ecosystem, namely intertidal mudflats. Our results indicate that mangroves are not in a steady state as has been recently claimed.

Key Words: basal area, ecosystem change, Hurricane Andrew, Hurricane Donna, Hurricane Wilma, Labor Day Storm, mortality, persistence, stability, steady state

INTRODUCTION

Hurricanes impact mangrove forests through three primary mechanisms: wind damage, storm surges, and sediment deposition. High winds snap and topple stems, break off branches, and defoliate the canopy (Smith et al. 1994, Doyle et al. 1995). As a storm surge comes ashore stems taller may be uprooted and knocked over, yet when covered by the surge, shorter stems may be protected from the hurricane's winds (Smith et al. 1994). Storm surges carry suspended sediment that is deposited on the forest floor as the surge recedes (Risi et al. 1995). The impact of sediment deposition in the forest depends on the depth and type of sediment deposited. Craighead and Gilbert (1962) and Ellison (1998) reported that very fine sediments deposited from hurricane storm surges resulted in mangrove mortality. The deposited materials interfere with root and soil gas exchange leading to eventual death of the trees. Prolonged flooding from water remaining after the storm surge may have a similar effect. The damage inflicted by each of these mechanisms often varies according to species of mangrove (Smith 1992, Woodroffe and Grime 1999, Imbert et al. 2000, Sherman et al. 2001). Descriptions of hurricane impacts on mangroves have been reported many times in the literature. Rollet (1981) listed >30 reports published prior to 1976. Since then, the number of descriptive articles has increased substantially.

Only recently, however, have studies appeared that followed mangrove forest recovery using repeated measures over time from permanent forest

plots. A value of a permanent plot network is that cumulative impacts can be measured accurately over time (Smith 2002). Imbert et al. (1996, 2000) studied the impact of Hurricane Hugo on the mangroves of Guadeloupe over an eight year period. Baldwin et al. (2001) examined regeneration dynamics in mangroves recovering from Hurricane Andrew in southeast Florida over a seven year period. Ward et al. (2006) worked on the southwest coast of Florida and reported on 13 yrs of recovery following Hurricane Andrew. Our study represents an opportunity to examine cumulative impacts of repeated hurricanes over time using permanent research plots in mangroves. We began work on the southwest coast of Florida immediately following the passage of Hurricane Andrew in August 1992 (Smith et al. 1994). All of the plots that were established following Hurricane Andrew were impacted by Hurricane Wilma in October 2005. Prior to our work, the southwest coastal Everglades had been struck by the Labor Day Storm of 1935 (Reimann 1940), and Hurricane Donna in 1960 (Craighead and Gilbert 1962). The Labor Day Storm was the first Saffir-Simpson Scale category 5 storm to hit the United States and Hurricane Donna was a category 4 (Houston and Powell 2003). These two storms followed relatively similar and parallel tracks. They moved northwest crossing the middle Florida Keys. Hurricane Donna crossed Cape Sable and then recurved and made landfall near Naples, Florida (Dunn 1961). The Labor Day Storm passed west of Cape Sable, then moved northward off the west Florida coastline and made landfall near Cedar Key (McDonald 1935). Hurricane Andrew made landfall on the southeast Florida coast as a Category 5 storm, crossed the Florida peninsula, and exited into the Gulf of Mexico just north of the Lostmans River as a Category 4 storm (Landsea et al. 2004). Andrew's forward motion was rapid ($\approx$ 35 km/hr) and it had a small, compact eye, only some 32 km in width (Mayfield et al. 1994). Hurricane Wilma approached south Florida from the southwest and made landfall near Everglades City as a Category 3 hurricane (Pasch et al. 2006, Beven et al. 2008). Wilma had an extremely large eye at landfall, with the northern eyewall passing south of Naples and the southern eyewall passing over a wide area from the Lostmans River south to Cape Sable (Pasch et al. 2006).

The objectives of our study were to: 1) accurately quantify the damage to mangroves from Hurricane Wilma both extensively over the landscape and intensively at selected sites; 2) relate forest damage to storm surge height and amount of sediment deposition; and 3) determine if damage from Wilma was related to damage from previous hurricanes. Additionally, because mangrove forest structure is the result of hydrology and geomorphic setting (Woodroffe 1994, Twilley and Rivera-Monroy 2005), we specifically tested the hypothesis that damage varied according to hydro-geomorphic type of mangrove forest (e.g., basin, island, riverine). Finally, we use historic reports concerning impacts from Hurricane Donna and the Labor Day Hurricane to examine cumulative impacts.

METHODS

Study Area

The study area comprises the far southwest coast of Florida from Flamingo north to Panther Key and lies mostly within Everglades National Park (Figure 1). Included are Big Sable Creek (BSC), a large tidal creek system with little freshwater runoff, and the Shark, Harney, Broad, Lostmans, and Chatham Rivers that drain the major freshwater sloughs of the Everglades. Approximately 10 to 20 km upstream from the Gulf of Mexico the rivers enter a series of shallow, interconnected bays. This mosaic of tidal rivers and bays breaks the coastal zone up into a network of large islands that comprise the southern portion of the 10,000 Islands (Schomer and Drew 1982). The intertidal vegetation is comprised primarily of mangrove forests with *Rhizophora mangle* L., *Laguncularia racemosa* (L.) Gaertn. f., and *Avicennia germinans* (L.) Stearn all present in varying abundance. The interiors of the largest islands are composed of brackish and freshwater marshes dominated by *Spartina bakeri* Merr., *Cladium jamaicense* Crantz, and *Juncus roemerianus* L. Tidal amplitudes range from 1–1.7 m and there is a marked annual variation in sea-level of 25 cm, with the high in October and the low in February (Stumpf and Haines 1998).

Storm Surges

We measured storm surge at four hydrological monitoring stations that comprise a downstream to upstream gradient along the Shark-Harney River system (Figure 1, see Smith 2004). The datum is NAVD88. Big Sable Creek (BSC) is in a short ($<$ 3 km) tidal creek on the northwest corner of Cape Sable. Some 200 m of mangrove forest and 200 m of mudflat separate it from the Gulf of Mexico. Shark River 3 (SH3) is located $\approx$ 3.9 km upstream from the gulf and is $\approx$ 50 m inland from the river. Shark River 4 (SH4) is on the Harney River, which, with the Shark, drains Tarpon Bay

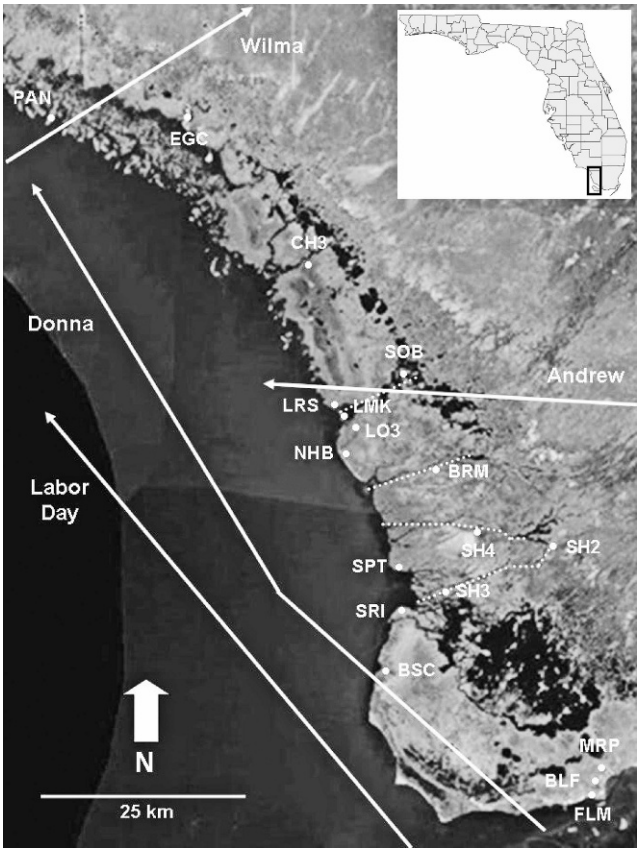

Figure 1. Locations of sampling sites and study transects along the southwest coast of Florida. Tracks of the four major hurricanes that impacted far south Florida are also shown: the "Labor Day" Storm (1935), Donna (1960), Andrew (1992) and Wilma (2005). Abbreviations for sites, from North to South, are: Panther Key (PAN), Everglades City (EGC), Chatham River 3 (CH3), Second Onion Bay (SOB), Lostmans Ranger Station (LRS), Lostmans Key (LMK), Lostmans River 3 (LO3), North Highland Beach (NHB), Broad River Middle (BRM), Shark River 4 (SH4), Shark River 2 (SH2), Shark Point (SPT), Shark River 3 (SH3), Shark River Island (SRI), Big Sable Creek (BSC), Mrazek Pond (MRP), Black Forest (BLF), and Flamingo (FLM). The four dashed lines show approximate locations of the sediment deposition transects from North to South: Lostmans, Broad, Harney and Shark Rivers. The fifth transect (BSC) is too short to depict.

and the main freshwater slough of the Everglades, Shark River Slough. SH4 is 9.5 km upstream and is 40 m inland from the river. The most upstream station, Shark River 2 (SH2), is adjacent to Tarpon Bay, some 19.7 km from the Gulf. It is 50 m inland from the shore of the bay. Data from two additional stations were also recovered, but are not in the NAVD88 datum. The northernmost station Chatham River 3 (CH3) is on the Chatham River, 4.1 km upstream from the Gulf and is 40 m away from the river. Lostmans River 3 (LO3) is on a side creek of the main Lostmans River and is 2.1 km upstream of the river mouth. It is 30 m from the creek. We supplemented the sparse instrumental record with extensive field surveys. We recorded heights of material that was stranded in the remaining forest canopy as a best estimate of surge height at each location.

Sediment Deposition

We measured sediment deposition from Hurricane Wilma along transects on the Lostmans, Broad, Harney, and Shark Rivers and at BSC (Figure 1). Each transect began where the river-creek entered the Gulf of Mexico and proceeded upstream until we could no longer find hurricane deposits, or the creek ended (e.g., BSC). At each site, we sampled near the river (within $\approx$ 10 m of the river bank) and away from the river (40–50 m into the mangrove forest). Sediment cores were collected with a Russian peat corer or PVC core tubes and the thickness of the Wilma layer was measured. Hurricane deposits are easily recognizable in the sedimentary record as they are composed of light grayish marine marl (Kang and Trefy 2003) on top of dark brown mangrove peat.

Mangrove Vegetation

The permanent forest plots were set up in basin, riverine, and overwash island type mangroves (Lugo and Snedaker 1974, Woodroffe 1992) in the months following the passage of Hurricane Andrew, in August 1992. The plots are circular with a post marking the center. All stems > 1.5 m in height were identified, measured for diameter at breast height (dbh) and mapped by recording their distance and bearing from the center post. Surviving stems were permanently tagged with aluminum tree-tags. Additional permanent plots had been established by October 2005 when Hurricane Wilma crossed the coastline. Many of these plots were in areas that were un-affected by Hurricane Andrew but that had been impacted by the Labor Day Storm and Hurricane Donna, such as Cape Sable and near Flamingo in the south of Everglades National Park (Reimann 1940, Craighead and Gilbert 1962, Baldwin et. al. 1995). The plots were placed in, or very near to, stands that Craighead had sampled and were located based on his notes (Craighead 1966a). In our plots, mortality, recruitment, and growth have been recorded for each survey interval since the plots have been established. Some of that data has recently been discussed (Ward et al. 2006) and will

not be duplicated here. Here we use data on % stem mortality and % basal area lost.

We calculated a first order approximation of the total mangrove forest area that had been catastrophically impacted by Hurricane Wilma using aerial photographs with a 0.33 m resolution, taken in January 2006 by PhotoScience, Inc. and geo-referenced by the Florida Fish and Wildlife Research Institute under contract with the National Park Service. We confined our analysis to the region of forest adjacent to the Gulf of Mexico as our field surveys indicated that was where most of the catastrophic damage had occurred. We define catastrophic damage as loss of $> 75\%$ of the stems fallen or broken (Smith et al. 1994). We visually interpreted the width of the damaged forest at regular intervals along the coast and simply multiplied average width by length of coast and summed for a total. Pre-Wilma photos were obtained for comparison (FDEP 2006). The photos were taken between October 2004 and March of 2005 and are rectified and geo-referenced with a resolution of 1 m.

Statistical Analyses

Sediment deposition data were analyzed using a multiple linear regression, with distance upstream, distance into the mangrove forest and river system (a categorical factor) as the independent variables (Kleinbaum and Kupper 1978). Percent mortality and percent basal area lost from Hurricane Wilma were used as dependent variables in a multiple linear regressions with depth of the storm surge and amount of sediment deposition, as independent variables. The influence of forest type (basin, riverine, island), hurricane (Andrew versus Wilma), and species (the three species of mangroves) on percent mortality and percent basal area lost was examined with a three factor, fixed-effects, ANOVA. Type III sums of squares were used because the design was un-balanced (i.e., there were an un-equal number of plots in each forest-type category).

RESULTS AND DISCUSSION

Storm Surges

The storm surge from Hurricane Wilma was lower in the northern and southern portions of the of the study area and highest in the middle. Beven et al. (2008) report a 2.1 m surge near Everglades City (EGC), while Soderqvist and Byrne (2007) measured a high water stain inside the Park Ranger Station at EGC of 1.78 m. At CH3 we recorded a 1.4 m surge. We estimate the maximum storm surge from Hurricane Wilma was 5.0 m, or higher, from Lostmans Ranger Station (LRS) to BSC, in the center of the study area. The LRS sat on a beach ridge 4.5 m in elevation on the north shore of the mouth of the river. Visible on a 1952 aerial photograph, it was most likely present in the mid 1920s when the Tropical Development Company was attempting to reclaim the area for agriculture (Tebeau 1968). It survived passage of the Labor Day Storm, Hurricane Donna, and Andrew's front and rear eye-walls. After Andrew we determined that it had not been flooded. Hurricane Wilma's storm surge swept it completely away (Figure 2). At the nearby LO3 hydrology station, we found sediment deposited on the top of the box housing the destroyed instruments, an elevation of 3.5 m. Entire trees were suspended 5 m up in the remains of the mangrove forest canopy at the North Highland Beach (NHB) permanent forest plot (Figure 3). Further south, at SH3, the hydrology platform was overtopped by the surge and vegetation had sediment stains 2.5 m above the ground surface. At BSC we found debris stranded at 3 m elevation in the remnant forest canopy. Weight of the logs had bent the stems upon which they rested, so our estimates are most likely low. In the Black Forest (BLF), a site located 2.4 km inland from the coast, sediment stains on vegetation indicated flooding of 0.6 m. At Flamingo (FLM) sediment stains on walls of buildings and tree stems indicated a surge depth of 2 m. Independent hind-casts of Wilma's surge based on the SLOSH model (NOAA 2006) agree surprisingly well with our field observations. The SLOSH model predicted slightly higher surges than we recorded: 5.5 m at LRS and NHB, 5.1 m at BSC, and 4.4 m at FLM. Predictions from the SLOSH model have a range of $\pm$ 20%.

Stage data from BSC show that Hurricane Wilma made landfall at low tide (Figure 4), and also indicate just how quickly water levels were rising. Water levels went from -1.44 to > 0.77 m, the last recorded data point, in 3 h. A gradient is also seen in the reduction of the surge as it propagated upstream in the Shark and Harney River system (BSC, SH 2–4, Figure 4). The two downstream stations were lost, but the recovered data indicate the rapid increase in stage. At SH4 the surge peaked at 1.02 m, while at SH2 the peak surge was reduced to 0.38 m (Figure 4).

A compilation of data from historical reports indicates that the pattern of flooding from Hurricane Andrew was relatively similar to that of Wilma, although lower (Figure 5). Rappaport (1993) and Mayfield et al. (1994) stated that Andrew produced

Figure 2. Hurricane Wilma removed the Lostmans River ranger station, which had survived previous storms.

storm tides of 1.5 m FLM and of 2.1 m at EGC. Risi et al. (1995) and Tedesco et al. (1995) estimated a storm tide of ≈ 4 m at NHB. Our observations following Andrew indicated that storm tides at LRS, LO3, and SH3 were lower (Figure 5). The path of Hurricane Donna combined with the curvature of the coastline, resulted in higher storm tides at the northern and southern ends of the study region and less in the center (Figure 5, see Craighead and Gilbert 1962, Harris 1963, Dunion et al. 2003). There are no estimates of storm tides for this region from the 1935 Labor Day Storm (McDonald 1935, Harris 1963).

Sediment Deposition

We found measurable sediment deposits from Hurricane Wilma from Lostmans River to Flamingo, a 70 km stretch of coastline. The deposits in general were < 10.0 cm thick. We found no Wilma storm deposits in the back bays further than 15.5 km from the Gulf of Mexico. At CH3 a sediment layer was observable but minimal

Figure 3. Permanent vegetation plot on North highland Beach (NHB) following Hurricane Wilma, January 16, 2006. The arrow indicates a tree stem, which was deposited 5 m above the sediment surface. The tree moved a minimum of 150 m, because that was the distance to the nearest beach line with trees.

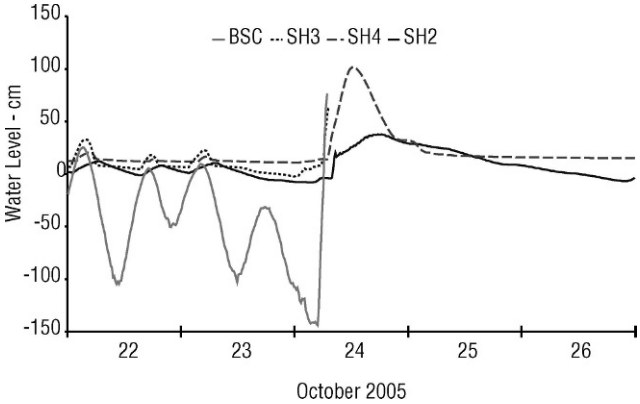

Figure 4. Water levels at Big Sable Creek (BSC) and Shark River sites 2–4 (SH2, SH3, SH4) recorded during the passage of Hurricane Wilma. Data are to the NAVD 88 datum. In southern Florida, an NAVD88 elevation of 0 is ≈ 26 cm above local Mean Sea Level (http://seacoos.org/Data%20Access%20and%20Mapping/wlimages/navd_to_msl.png/image_view).

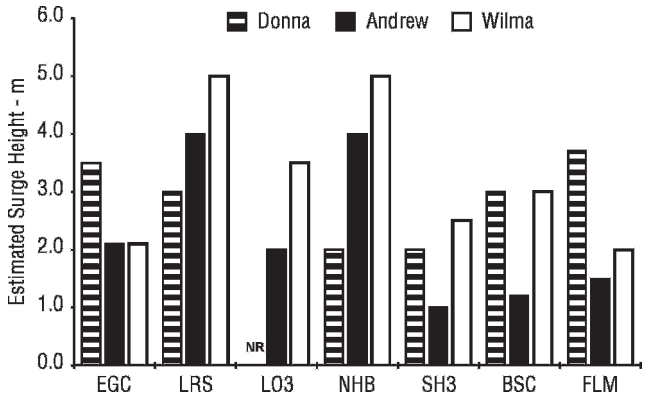

Figure 5. Estimated storm surge heights from Hurricanes Donna, Andrew and Wilma for seven locations along a north to south transect on the southwest Florida coastline. NR = Not reported.

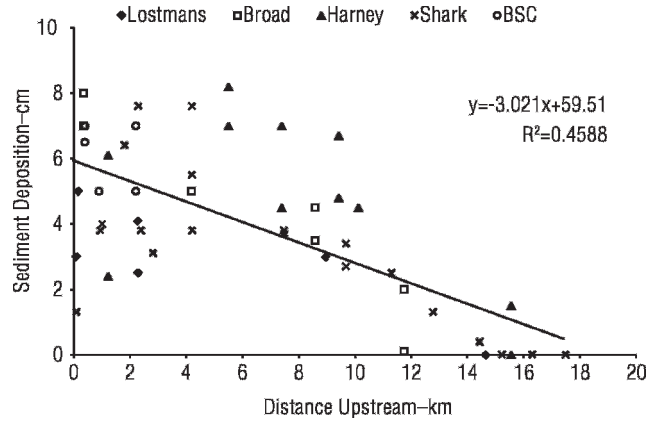

Figure 6. Sediment deposition (cm) from Hurricane Wilma as a function of distance upstream from the Gulf of Mexico (km) for five tidal rivers and creeks in Everglades National Park. There were no differences between rivers so a single regression line is given. Key for symbols: Lostmans (◆), Broad (□), Harney (▲), Shark (X) and Big Sable Creek (O).

(< 0.1 cm). To the south at FLM we recorded a 3.0 cm sediment layer. For our transects, analysis revealed that sediment deposition was not different between river systems, therefore a single regression line could be used. Sediment deposition was significantly related to distance upstream, which accounted for 45.9% of the variance in the data ($F_{1,52} = 48.7$, $p < 0.001$, Figure 6). Distance into the forest accounted for an additional 5.1% of the variance in the dataset ($F_{1,52} = 5.5$, $p < 0.05$).

As Hurricane Andrew exited the coast and moved offshore the ensuing storm surge deposited sediment along a 13 km length of coast from Highland Beach to Shark Point (Risi et al. 1995). The deposits reached 10 km inland and impacted an area of ≈ 110 km^2. In the mangrove forests inland from NHB the sediment layer was 5–7 cm thick (Risi et al. 1995). On the natural levee bordering the Broad River, 5 km upstream from the gulf, the deposits were 11–17 cm deep (Risi et al. 1995). Although the depositional layers we measured after Wilma were less than those reported by Risi et al. (1995) for Andrew, the total area impacted by Hurricane Wilma's storm deposits was about 400 km^2, or 3.5 times larger than the area affected by Hurricane Andrew.

Impacts to Mangroves from Hurricane Wilma

Catastrophic damage to the mangrove forest was mainly confined to a narrow band (50–500 m wide) adjacent to the Gulf of Mexico (Figure 7). It extends for 50 km, starting 5 km south of BSC and extending to ≈ 10 km north of LRS. A few isolated areas of catastrophic damage were found to the north and south of this core region. The width of the band averages 250 m, meaning that, conservatively, 1,250 ha of mangrove forest suffered catastrophic disturbance during Hurricane Wilma.

At the plot and species level, % stem mortality and % basal area lost, were highly variable, ranging from 0 to 100%. Damage was not significantly correlated with either the amount of sediment deposited, distance from open water or height of the storm surge, at either the whole plot level or by species of mangrove.

Comparing Hurricanes Andrew and Wilma

When the plots were grouped by hydro-geomorphic category (basin, riverine, and overwash island), interesting patterns emerged. For % stem mortality and % basal area lost, forest type accounted for 7.9% and 11.8% of the variance, respectively (Figure 8, Table 1). No differences among species or between Hurricanes Andrew and Wilma were found. However, for both dependant variables, the forest type by hurricane interaction terms were highly significant, accounting for 18% and 22% of the variance, respectively (Figure 8, Table 1). This result indicates that the two hurricanes had differential impacts on the three forests types, and in fact represents the previous impact of Hurricane Andrew on the forests. This is well illustrated for the basin type forests. One basin forest (NHB) was catastrophically impacted by both storms. The other three (BF1 & 2, MRP) were outside of the influence of Andrew but were heavily damaged by Wilma. Imbert et al. (1996, 2000) reported that basin forests

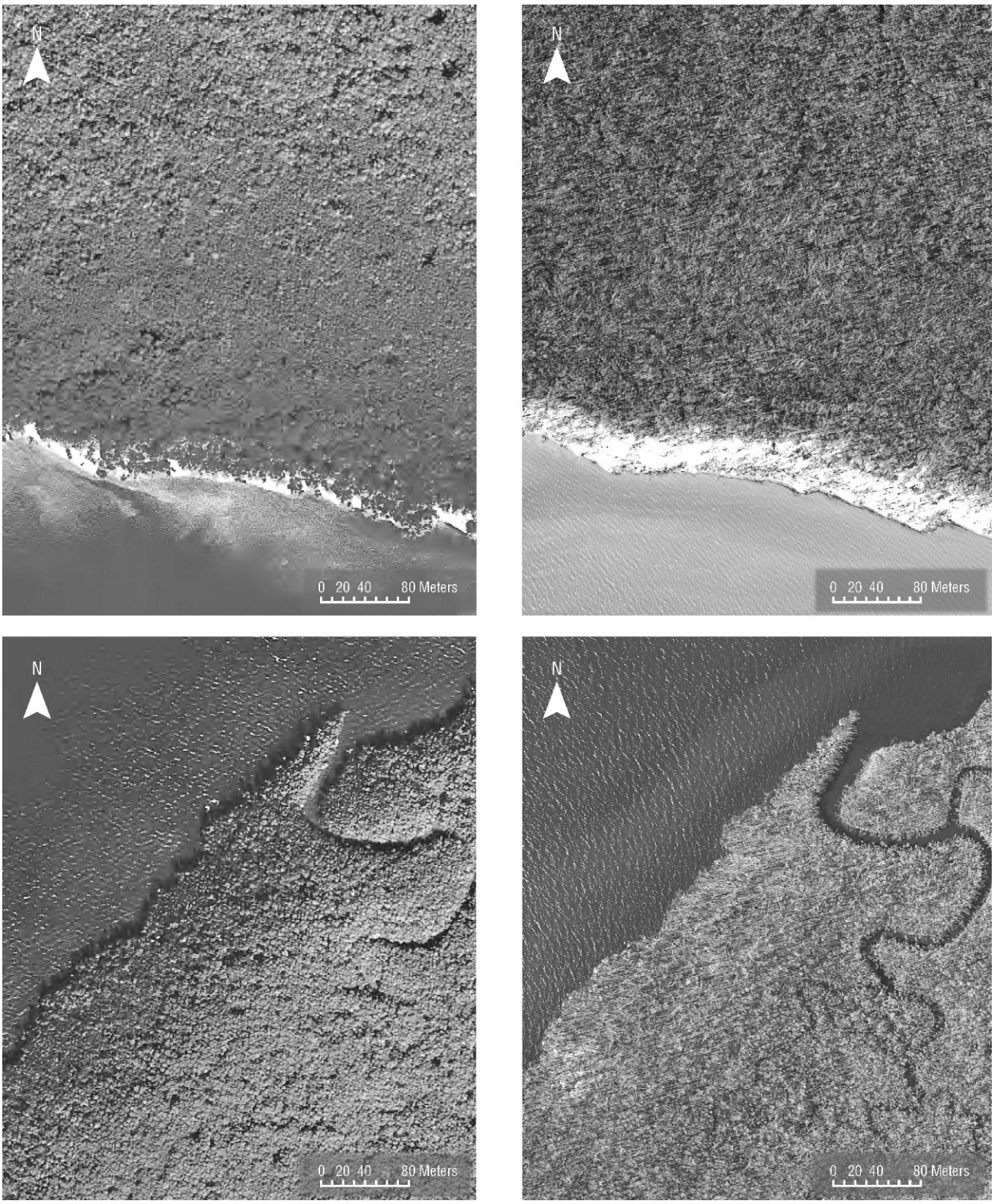

Figure 7. These pairs of aerial photos show Shark Point (SHP, upper panels) and Little Shark Island (LSI, lower panel) before (left) and after (right) the passage of Hurricane Wilma. The differences in texture in the images after the hurricane (right panels) indicate that tree stems are down. The scale is 1:2000.

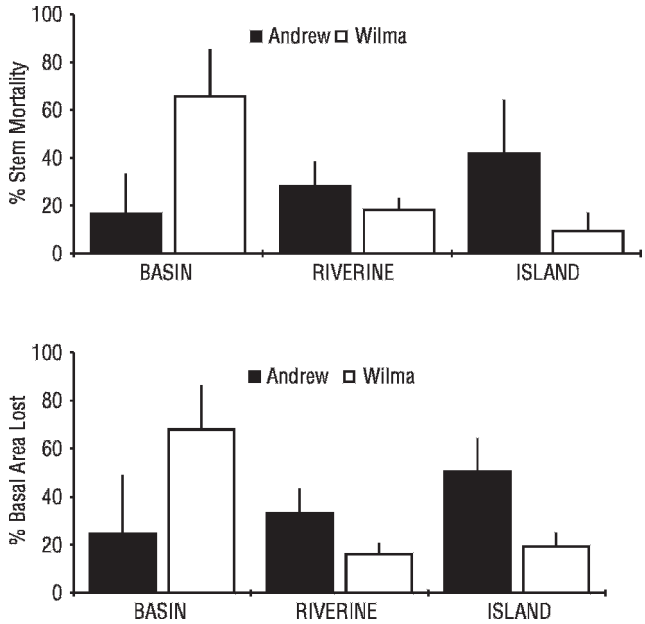

Figure 8. Graphic representation of the Forest Type by Hurricane interaction for % stem mortality (upper) and % basal area lost (lower). The data have been averaged over the three species of mangrove. Values are $\bar{X} \pm 1$SE.

on Guadeloupe appeared more susceptible to disturbance than fringing forests. Basin forests are depressions and hold water (Twilley and Chen 1998). It could be that floodwaters from a hurricane remain in the basins long enough to result in suffocation of the plant roots and death of the trees. Another possibility is differences in sediment characteristics among forest types, a factor we are currently examining. Few authors have reported on the shear strength or cohesiveness of mangrove sediments. Soil shear strength relates to the amount of force, or stress, needed to deform, or break, a soil body (Poulos 1981). Sediments in the basins may be less cohesive resulting in a tendency for trees to be more easily toppled by storm surges or high winds. Cahoon et al. (2003) examined the impacts of Hurricane Mitch on mangrove forests in the Bay Islands of Honduras. They reported that fringing mangroves had significantly higher shear strengths at the surface and at 25 cm depth, than did basin forests. Additionally, forests suffering low impacts from Mitch had higher shear strength than forests with high storm damage (Cahooon et al. 2003).

Mangroves, Previous Large-Scale Disturbances, and Cumulative Impacts

We have already seen that Hurricane Andrew inflicted severe disturbance to some forests in our study area. Craighead and colleagues provided semi-quantitative notes on mortality from Hurricane Donna (Craighead and Gilbert 1962, Craighead 1966a, 1966b, 1971). For the coastal strip from the Shark River to EGC, 30–50% mortality was reported (Craighead and Gilbert 1962, Craighead 1966b). In the southern portion of the study area, mortality from Donna was higher: 100% at MRP, 80% at BF1 and 2, and 90–100% for interior location at BSC (Figure 9). Given that Donna passed over Cape Sable (Dunn 1960), this would be expected. The Labor Day Storm also severely influenced the Cape Sable region. Reimann (1940) described the mangroves along the Shark and Harney Rivers and reported that the mangroves in the lower Shark and Harney rivers had survived the 1935 storm and were in an intact and healthy condition. In reference to the Cape Sable area he stated that the mangrove forests were utterly devastated. It appears that the near total destruction of the mangrove forests on parts of Cape Sable initiated the formation of what are now extensive mudflats (Figure 10). Aerial photos from 1928 indicate the presence of mangrove forests to the edge of the creek network. In 1952 extensive mudflats existed. Bischoff (1995) postulated that it was disturbance from the Labor Day hurricane that initiated mudflat formation and we concur. Total removal of a mangrove forest canopy results in a phenomena called peat collapse and rapid loss in surface elevation (Cahoon et al. 2003). At several of our sites tree mortality is ongoing as heavily damaged and defoliated stems continue to perish and we are observing decreases in surface elevation (Smith, unpubl. data).

What is clear, however, is that mangroves are not in equilibrium as some authors have recently claimed (Alongi 2008). Repeated disturbances can, and have, changed some mangrove forests into a different ecosystem. A recent modeling study has shown that transitions from one vegetation community into another can occur rapidly and persist for $>$ 100 years due to salinity intrusions from storm surges (Teh et al. 2008). At BSC, mangroves have become intertidal mudflats. Considering that sea-level is rising at a rapid pace ($>$ 2.2 mm yr^{-1}) in south Florida (Maul and Martin 1993) return of the mudflats to a mangrove ecosystem state is unlikely. Several important questions remain to be answered: Are there thresholds of cumulative impacts that result in a change of state, and if so, what are they? How much mangrove forest will be converted to mudflats due to the disturbance from Hurricane Wilma? Are there management interventions (e.g., planting) that can be taken to prevent state changes?

Table 1. Analysis of Variance results for % Stem Mortality and % Basal Area Lost. % Variance gives the percentage of total variance explained by a given factor or interaction term. Df = degrees of freedom.

% Stem Mortality	Df	Sum of Squares	% Variance	F value	P
Forest Type (FT)	2	8074	7.91	4.83	0.05
Hurricane (H)	1	354	0.35	0.42	ns
Species (S)	2	2074	2.03	1.23	ns
FT × H	2	18986	18.59	11.31	0.01
FT × S	4	1481	1.45	0.44	ns
H × S	2	1411	1.38	0.84	ns
FT × H × S	4	373	0.37	0.11	ns
Residual	66	55351	54.20		
% Basal Area Lost	**Df**	**Sum of Squares**	**% Variance**	**F value**	**P**
Forest Type (FT)	2	11315	11.08	6.29	0.05
Hurricane (H)	1	148	0.14	0.16	ns
Species (S)	2	2241	2.19	1.25	ns
FT × H	2	22515	22.05	12.52	0.01
FT × S	4	1802	1.75	0.50	ns
H × S	2	1834	1.80	1.02	ns
FT × H × S	4	2941	2.88	0.82	ns
Residual	66	59321	58.09		

What differences in hydro-geomorphic types of mangroves result in differential susceptibilities to disturbance?

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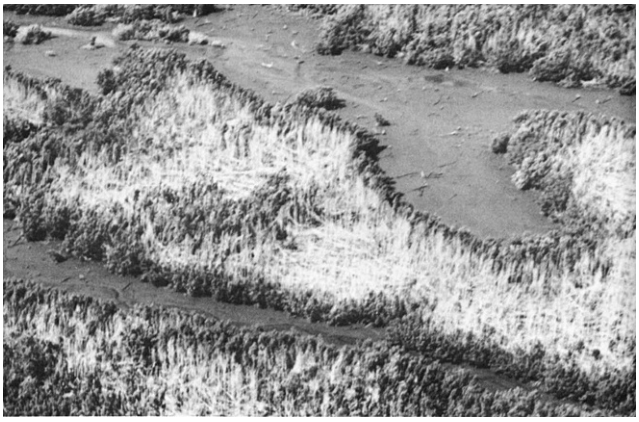

Figure 9. This oblique aerial photograph shows a portion of the Big Sable Creek (BSC) study site in November 1960, two months after the passage of Hurricane Donna. Fringing mangroves appear to have survived the hurricane, whereas trees in interior locations have experienced catastrophic mortality. Note the extensive barren mudflats in the upper portions of the photo. This picture appeared on page 44 of Craighead (1971) and is used courtesy of the archives at Everglades NP.

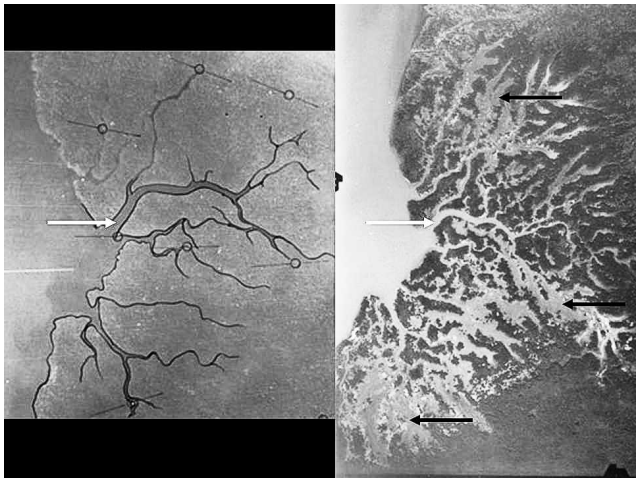

Figure 10. Big Sable Creek is shown in these two aerial photos. On the left is a photo taken March 29, 1928 by the U.S. Army Air Corps for the U.S. Coast and Geodetic Survey. It was used in the compilation of Topographic Sheet T-4460 (see Smith et al. 2002 for details). On the right is a portion of photo 4–107 from March 16, 1952 taken by the USGS (courtesy EROS Data Center). White arrows point to Big Sable Creek itself. The Black arrows indicate extensive mudflats.

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