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Ecological Impacts of Hurricane Ivan on the Gulf Coast of Alabama: A Remote Sensing Study

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ABSTRACT

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Hurricane Ivan made landfall near Gulf Shores, Alabama, as a category 3 storm in 2004, causing a storm surge of > 3.0 m and massive tree mortality in the forest around the Shelby Lakes in Gulf State Park. We documented the ecological impacts of Hurricane Ivan by means of remote sensing techniques using Landsat 5 images, coupled with a ground survey of tree mortality and damage patterns. NDVI-based land cover classifications of pre- and post-Ivan images reveal that 44% of the forest in the study area was killed or heavily damaged by the storm. Ground survey data suggest that the belt delineated as dead or highly damaged vegetation is characterized by low elevations (< 3 m) and high tree mortality (50-100% dead trees); whereas forested areas occurring on higher grounds (> 3 m elevation) suffered lower (< 50%) tree mortality. The damage pattern strongly suggests that saltwater intrusion and storm surge flooding, rather than wind damage, was the main cause for massive tree mortality around the Shelby Lakes. Results from this study are useful for interpreting the proxy records and informing ongoing paleotempestological investigations in coastal Alabama.

ADDITIONAL INDEX WORDS: *tree mortality, storm surge, paleotempestology, coastal lakes*

INTRODUCTION

Hurricanes are important agents of ecological disturbance and succession in coastal ecosystems. During the past five years, the northern Gulf of Mexico coast has been struck by several intense hurricanes, including Ivan (2004), Katrina (2005), Rita (2005), Gustav (2008), and Ike (2008), resulting in major losses of life and property in the coastal states from Texas to the Florida Panhandle. The first in this recent series of storms is Hurricane Ivan, which made landfall as a Saffir-Simpson category 3 storm on the Gulf Coast of Alabama on September 16, 2004. Ivan offers an excellent opportunity for studying the ecological and geological impacts of hurricanes in the context of paleotempestology, because it directly hit an area where several paleo-hurricane proxy records have been produced from coastal lake sediments (LIU AND FEARN, 1993; LIU, 2004; LIU *et al.*, 2008; LAMBERT *et al.*, 2008), including a pollen and charcoal record of vegetation responses to hurricanes and fires (LIU *et al.*, 2008). In this study, we used remote sensing techniques, coupled with ground-truthing data obtained by a vegetation survey, to document the effects of Hurricane Ivan on the coastal ecosystems of Gulf State Park in Gulf Shores, Alabama. Remote sensing techniques have recently been applied to assess hurricane damage to coastal ecosystems (CABLK *et al.*, 1994; RAMSEY *et al.*, 1997, 1998, 2001; BOUTET AND WEISHAMPEL, 2003; WANG, 2004; AYALA-SILVA AND TWUMASI, 2004; KIAGE *et al.*, 2005; GILLESPIE *et al.*, 2006; CHAMBERS *et al.*, 2007). Our paper applies remote sensing techniques to an area on the Gulf Coast where information on the biophysical impacts of a modern intense hurricane can be used to inform ongoing paleotempestological studies and aid the interpretation of paleoecological proxy records.

STUDY AREA

Gulf State Park (30° 15' 58" N, 87° 38' 01" W) (Figure 1) contains a suite of three coastal lakes (Lake Shelby, Middle Lake, Little Lake—also collectively known as the Shelby Lakes) which have been the subject of paleotempestological studies during the past 15 years (LIU AND FEARN, 1993; LIU *et al.*, 2008). All three lakes are separated from the Gulf of Mexico by a barrier beach and a beach ridge plain, on which are sand dunes rising to approximately 2-4 meters in elevation. Vegetation around the lakes is a subtropical pine-hardwood mixed forest, with scrub oak and pines growing on the beach ridges. Non-forested wetlands (primarily brackish and fresh marshes) occur on the western and eastern sides of Lake Shelby and around the southern end of Middle Lake, where the elevations are low.

Hurricane Ivan made landfall as a category 3 storm just to the west of Gulf Shores, bringing with it maximum sustained winds of 120 mph and a storm surge of 10-12 feet (ca. 3.0-3.6 m) along the Alabama Gulf Coast. The entire coastal plain around the Shelby Lakes was inundated by sea water, which accumulated in the low lying areas for days before it receded. Ivan's strong wind and storm surge flooding resulted in significant damages and mortality to the forest vegetation around the lakes. Attesting to the extent of tree mortality, the forest landscape at the Shelby Lakes still looked brown in the summer of 2005, a year after Ivan (Figure 2).

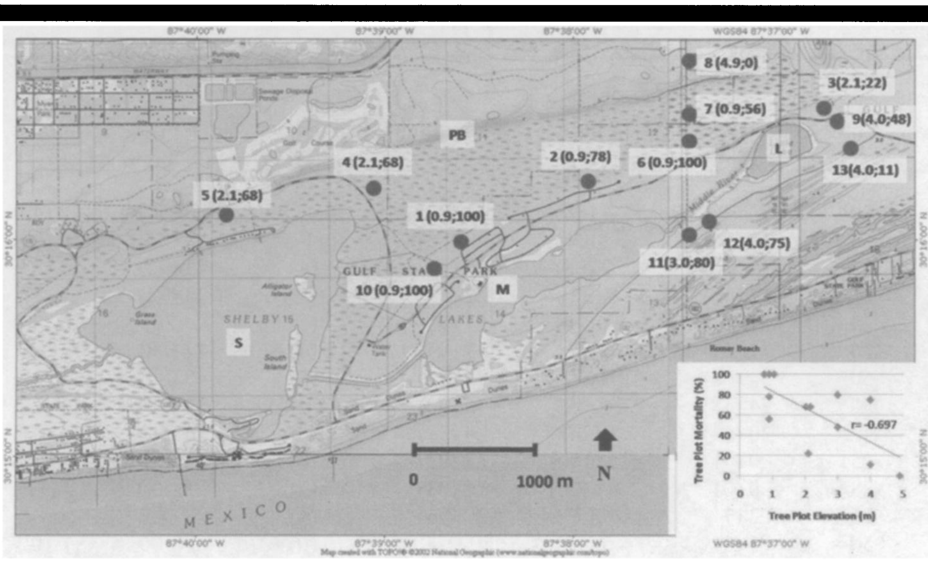

Figure 1: Gulf State Park, with Lake Shelby (labeled S), Middle Lake (M), and Little Lake (L). Pamlico Barrier is labeled PB. Tree plot centers are designated with a dot with descriptive information inside the parentheses (elevation in meters; tree mortality percentage). Regression (bottom right – inset) indicates strong relationship between tree mortality and tree plot elevation. Map created with TOPO! © National Geographic Maps

METHODS

Remote Sensing

Two Landsat 5 images (30 m resolution, path 020, row 039, GeoTiff format), dated 20 July 2004 (pre-Ivan) and 7 July 2005 (post-Ivan), were used for this study. The post-hurricane image was taken about 9 ½ months after the hurricane to ensure that vegetation that was permanently, not temporarily, destroyed was captured. The images were input into an eccentricity model followed by a radiance/reflectance model for atmospheric and radiometric correction. Geometric correction was performed on the pre- and post-hurricane image to ensure that the images are aligned to each other and reference images.

Vegetation indices are frequently used in hurricane disturbance ecological studies (AYALA-SILVA AND TWUMASI, 2004) and present a fitting complement to the land cover classifications to help verify the degree and spatial characteristics in tree damage. The Normalized Difference Vegetation Index (NDVI) was computed for both the pre- and post-storm images. An image difference was created between the pre-Ivan and post-Ivan NDVI images, often an effective means to discover the extent and degree of damage (RAMSEY *et al.*, 2001).

Figure 2: Photograph taken during summer of 2005 of forest between Lake Shelby and Middle Lake. Most trees are standing with branches intact, with only a few trees toppled.

A hybrid classification method (TØMMERVIK *et al.*, 2003; LATIFOVIC *et al.*, 2004) incorporating both supervised and unsupervised classification techniques using ERDAS Imagine was used to classify the land cover pattern in the Gulf State Park based on the Landsat images. The clump/eliminate functions were used to reduce out-of-place pixels by grouping and eliminating them. A matrix function was executed between the final pre- and post-hurricane classified images to represent any land cover changes between the two images. Accuracy assessment using aerial phototraphy as reference data from before Ivan (1992/1997), soon after Ivan (28 September 2004) and much after Ivan (September 2006) were performed on the pre- and post-hurricane images to ensure classification accuracy at or near 85% (CONGALTON AND GREEN, 1999).

The land cover classification scheme used follows ANDERSON *et al.* (1976). The pre-storm image consisted of five classes: forest, non-forested wetland, barren, urban, and water. The post-hurricane image included an additional class of dead/severely sensing data showing a significant decrease in NDVI values after the storm, as well as vegetation survey data suggesting high degree of tree mortality (50-100% dead trees).

Tree Survey

A field survey (Figure 1) was performed in October 2006 and January 2007 to assess the degree and pattern of tree damages caused by Ivan, particularly as a function of topographic differences. Thirteen plots were selected for this tree survey. For each plot an arbitrary center tree was marked. The remaining trees of the plot were marked by emanating away from this center tree. For areas with dense undergrowth, 25-30 trees were counted. For most areas the undergrowth was not dense; there 50 trees were counted. For each tree it was determined if it was: 1) dead or

Table 1: *Tree plot information grouped by elevation. Displays # of trees for each plot and data regarding tree type (pine, hardwood), status (standing, broken), branches (intact, not intact) and mortality.*

Plot	Elev. (ft)	Elev. (m)	# of trees	# hardwood (%)	# pine (%)	# standing (%)	# broken/not stand (%)	# br. intact (%)	# br. not intact (%)	# dead (%)
1	3	0.9	50	6 (12)	44 (88)	41 (82)	9 (18)	30 (60)	20 (40)	**50 (100)**
2	3	0.9	50	12 (24)	38 (76)	43 (86)	7 (14)	40 (80)	10 (20)	**39 (78)**
6	3	0.9	25	3 (12)	22 (88)	24 (96)	1 (4)	23 (92)	2 (8)	**25 (100)**
7	3	0.9	25	17 (68)	8 (32)	22 (88)	3 (12)	23 (92)	2 (8)	**14 (56)**
10	3	0.9	25	1 (4)	24 (96)	23 (92)	2 (8)	5 (20)	20 (80)	**25 (100)**
3	7	2.1	50	27 (54)	23 (46)	47 (94)	3 (6)	44 (88)	6 (12)	**11 (22)**
4	7	2.1	50	34 (68)	16 (32)	47 (94)	3 (6)	40 (80)	10 (20)	**34 (68)**
5	7	2.1	50	24 (48)	26 (52)	45 (90)	5 (10)	39 (78)	11 (22)	**34 (68)**
9	10	3.0	27	20 (74)	7 (26)	24 (89)	3 (11)	16 (59)	11 (41)	**13 (48)**
11	10	3.0	25	0 (0)	25 (100)	23 (92)	2 (8)	3 (12)	22 (88)	**20 (80)**
12	13	4.0	28	0 (0)	28 (100)	26 (93)	2 (7)	25 (89)	3 (11)	**21 (75)**
13	13	4.0	28	2 (7)	26 (93)	27 (96)	1 (4)	23 (82)	5 (18)	**3 (11)**
8	16	4.9	50	4 (8)	46 (92)	50 (100)	0 (0)	50 (100)	0 (0)	**0 (0)**
	Totals:		**483**	**150**	**333**	**442**	**41**	**361**	**122**	**289**

alive, 2) a pine or hardwood, 3) standing/leaning or broken, and 4) possessing branches that were intact or snapped off. Phi coefficients (Sheskin, 1997) were used to determine the association between nominal variables. For each plot approximate elevations were obtained from National Geographic's TOPO software along with Google Earth, both of which give accurate and consistent topographic measurements. Areas of low (0.9-2.1 m or 3-7 ft), medium (~2.1-4.3 m, or 8-14 ft), and high elevation (~4.3+ m, or 15+ ft) were included in the sampling design.

RESULTS AND DISCUSSION

The results of the tree plot survey are listed in Table 1. Figure 1 shows that tree mortality decreases with increasing elevation ($r = -0.697$, significant at the 0.01 level). Thus, trees growing at lower elevations suffered greater mortality than those growing at higher elevations. The cross-tabulation of binary statistics (pine/hardwood; standing/not standing or broken; branches intact/not intact) and the mortality variable is shown in Table 2. Among 333 pine trees counted, 62% were dead; whereas the mortality rate for hardwood trees was 56%. The phi value of 0.052 with a significance level of 0.249 suggests that no meaningful relationship exists between tree type and mortality. Among those trees still standing ($n = 442$), slightly over half (56%) are dead. Similarly, among those trees with unbroken or intact branches ($n = 361$), half (50%) are dead. The phi values between the standing/not standing or broken (-0.234) and branches intact/not intact (-0.36) binary variables and the dead/alive variable suggests a weak but significant relationship. Thus, the vegetation survey data show that trees growing in low-lying areas were more likely to be killed than those growing in higher grounds, and that a significant portion of trees that were dead were still standing and had unbroken branches. These results strongly suggest that the storm surge and saltwater inundation, rather than strong winds, was the main cause of tree mortality in Gulf State Park.

Table 2: *Cross-tabulation of binary variables (pine/hardwood, standing/not standing, branches intact/not intact) with the mortality variable.*

	Dead	Alive	Dead (%)	Totals
Pine	205	128	62	**333**
Hardwood	84	66	56	**150**
Totals	**289**	**194**	**60**	**483**
	Dead	**Alive**	**Dead (%)**	**Totals**
Standing	249	193	56	**442**
Broken	40	1	98	**41**
Totals	**289**	**194**	**60**	**483**
	Dead	**Alive**	**Dead (%)**	**Totals**
Intact	179	182	50	**361**
Not intact	110	12	90	**122**
Totals	**289**	**194**	**60**	**483**

The pre-Ivan and post-Ivan land cover classification results are shown in Figure 3 In the pre-Ivan classification, the distribution of the five land cover categories (water, barren, urban, forest, non-forested wetlands) is clearly and accurately delineated. Forest occurs extensively to the north of the three lakes, as well as to the southeast of Middle Lake. The non-forest wetland category depicts the occurrence of brackish marshes to the west and east of Lake Shelby, as well as in the low-lying areas adjacent to the southern end of Middle Lake. Areas classified as urban land cover correspond with paved or other artificial surfaces, such as buildings, roads, parking lots, camp grounds (e.g., north of Middle Lake), and golf courses (e.g., north of Lake Shelby). The barren areas mainly represent sandy beaches, beach ridges, and dune fields. In the post-Ivan classification, the most remarkable feature is a large belt of dead or highly damaged vegetation, which mainly occurs to the north of the three lakes, but smaller belts or patches occur also to the south of Middle Lake and in the swales between beach ridges south of Little Lake. This land cover category corresponds to areas where the NDVI values decreased from those of healthy forest (NDVI values ~0.6-0.7) to those more indicative of wetlands or less healthy vegetation (~0.1-0.4). Its northern boundary is clearly defined by the Pamlico Barrier, a ridge that marks the paleo-shoreline of the last interglacial. Field observations and our vegetation survey data further support that

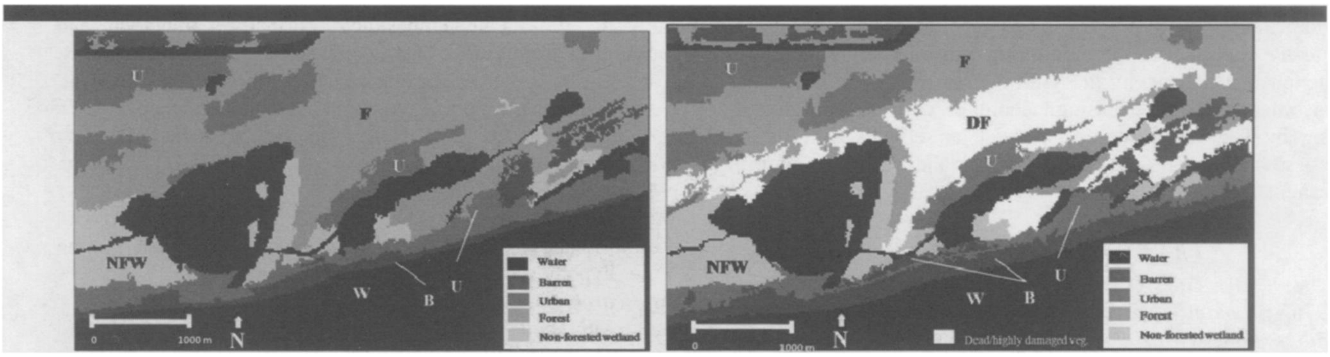

Figure 3: Final land cover classifications for Gulf State Park approximately three months before (left) and nine months after (right) Hurricane Ivan. Coding is included for ease in land cover depiction (W-water, B-barren, U-urban, F-forest, NFW-non forested wetland, DF-dead, or damaged forest).

the areas classified as dead or highly damaged vegetation are low-lying areas (< 3m elevations) where tree mortality was 50-100% (Figure 1), thus resulting in a highly damaged or open canopy. On the other hand, the forested areas not classified as dead or highly damaged vegetation typically occupy higher grounds (> 3 m elevations) and are characterized by <50% tree mortality. In these areas the canopy was mostly intact and the leaves/needles were green and healthy, despite the occurrence of scattered dead trees. Another notable change between the pre- and post-Ivan classifications is that the coastal strip of barren land cover became much wider after the storm. This clearly reflects the landward sand deposition from the beach and dune fields due to the overwash processes.

Table 3 shows the areal change in different land cover types before and after the storm. The most remarkable change is that the forest area decreased from 1,108 to 622 hectares—a reduction of 44%, which is now classified as dead or highly damaged vegetation in the post-Ivan image. The massive tree mortality would result in the accumulation of an enormous amount of dead biomass over time, which would become fuel for large wildfires (MYERS AND VAN LEAR, 1998). Sedimentary proxy record coupled with pollen and microscopic charcoal evidence from a sediment core extracted from Little Lake has revealed that major fires occurred near the Shelby Lakes more than a dozen times during the last 1,200 years, but some of the largest fires occurred after intense hurricane strikes as predicted by the hurricane-fire interaction hypothesis (LIU *et al.*, 2008).

The barren areas—mainly covered by sand after the storm—increased from 194 to 288 hectares, a gain of 48% due to widespread sand deposition by overwash processes (Table 3).

Table 3: *Land cover change statistics produced from the matrix image.*

land cover	pre-Ivan (hectares)	post-Ivan (hectares)	change (hectares)	percent change
barren	194	288	94	48%
urban	470	427	-43	-9%
forest	1108	622	-486	-44%
forest (damaged)	0	484	484	N/A

Much sand was deposited on roads and built areas, as suggested by the 9% decrease in the areas classified as urban after the storm. Undoubtedly some of the sand was deposited in the nearshore areas of the three Shelby Lakes, forming an overwash sand layer that was identified in the sedimentary proxy record recovered from these lakes (BIANCHETTE, 2007). Thus, the results of this remote sensing study can also inform paleotempestological investigations in coastal Alabama by documenting the provenance of sand found in the proxy record.

CONCLUSIONS

This paper documents the ecological impacts of Hurricane Ivan at the landscape level around the Shelby Lakes in Alabama by means of remote sensing technique coupled with a vegetation survey on the ground. Based on pre- and post-Ivan Landsat images, the remote sensing study shows that 44% of the forest in the vicinity of Gulf State Park was killed or heavily damaged by the storm. The belt of dead or highly damaged forest, which is characterized by >50% tree mortality, corresponds with the low-lying areas at < 3 m elevation in the state park, whereas the forest growing at higher elevations (> 3 m elevation) generally suffered lower (< 50%) tree mortality. The field evidence strongly suggests that saltwater intrusion and storm surge inundation, rather than wind damage, was the main cause of massive tree mortality and vegetation damage in coastal Alabama. The storm surge created a fragmented landscape in terms of tree survivability, with areas of lower elevation more damaged than areas of higher topography. The pattern of wind-induced mortality would have been very different, with higher mortality occurring in higher grounds where the trees are more exposed to strong winds (LUGO AND SCATENA, 1996). Instead, our remote sensing results coupled with the ground survey data show that the belt of dead or highly damaged forest was mainly confined to the swampy low-lying areas south of the Pamlico Barrier, whereas tree survivability was high in areas on and behind that elevated barrier ridge. Additional support for the flood damage scenario comes from the tree survey data showing that a significant portion of the dead trees are still standing or having unbroken branches, which are inconsistent with wind damage. Storm surge flooding is able to kill the trees without toppling them or causing them to lose their branches. Topography has been shown to be a major factor determining flood extent and patterning (BATES AND DE ROO, 2000; SANYAL AND LU, 2004; WEBSTER *et al.*, 2004) as well as vegetation health during storm surge flooding (KIAGE *et al.*, 2005).

Accurate assessment of hurricane damage to coastal ecosystems is critically important to the monitoring and forecasting of future climate change effects in the Gulf Coast region. Our study demonstrates that remote sensing techniques, coupled with ground truthing by vegetation surveys, provide an effective means of rapid assessment for ecosystem damage and recovery after a hurricane.

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