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Monitoring Vegetation Response to Episodic Disturbance Events by Using Multitemporal Vegetation Indices

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ABSTRACT

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Normalized Difference Vegetation Index (NDVI) derived from MODerate-resolution Imaging Spectroradiometer (MODIS) satellite imagery and land/water assessments from Landsat Thematic Mapper (TM) imagery were used to quantify the extent and severity of damage and subsequent recovery after Hurricanes Katrina and Rita of 2005 within the vegetation communities of Louisiana's coastal wetlands. Field data on species composition and total live cover were collected from 232 unique plots during multiple time periods to corroborate changes in NDVI values over time. A prehurricane 5-year baseline time series clearly identified NDVI values by habitat type, suggesting the sensitivity of NDVI to assess and monitor phenological changes in coastal wetland habitats. Monthly data from March 2005 to November 2006 were compared to the baseline average to create a departure from average statistic. Departures suggest that over 33% (4,714 km^2) of the prestorm, coastal wetlands experienced a substantial decline in the density and vigor of vegetation by October 2005 (poststorm), mostly in the east and west regions, where landfalls of Hurricanes Katrina and Rita occurred. The percentage of area of persistent vegetation damage due to long-lasting formation of new open water was 91.8% in the east and 81.0% and 29.0% in the central and west regions, respectively. Although below average NDVI values were observed in most marsh communities through November 2006, recovery of vegetation was evident. Results indicated that impacts and recovery from large episodic disturbance events that influence multiple habitat types can be accurately determined using NDVI, especially when integrated with assessments of physical landscape changes and field verifications.

ADDITIONAL INDEX WORDS: *Change detection, coastal wetlands, Hurricane Katrina, Hurricane Rita, marsh vegetation communities, MODIS, multitemporal imagery, NDVI, spectral vegetation indices.*

INTRODUCTION

Hurricanes are significant episodic disturbances that impact vegetated landscapes in coastal areas (Conner *et al.*, 1989; Guntenspergen *et al.*, 1995; Keim, Muller, and Stone, 2007). Hurricane impacts result from physical scouring and displacement of marsh (Barras, 2007a; Morgan, Nichols, and Wright, 1958) as well as physiological effects such as saltwater intrusion and flooding stress (Guntenspergen *et al.*, 1995; Shiflet, 1963; Steyer *et al.*, 2007; Wright, Swaye, and Coleman, 1970). These effects have been well described at local, site-specific scales but not at coastwide scales, in part because of the inability to acquire comprehensive coastal field measurements. Remotely sensed monitoring can resolve this limitation by providing a platform by which large spatial areas can be assessed repeatedly over time.

Remote sensing of canopy reflectance using vegetation indices has become one of the most valuable and readily available tools for regional- and ecosystem-scale research and management applications. The Normalized Difference Vegetation Index (NDVI) is an index to detect live, green plant canopies. Relationships between NDVI and vegetation productivity, leaf area index, fraction of radiation intercepted, and canopy cover has been developed for many ecosystems and allows for the detection of seasonal phenologies and possible stressors that influence these phenologies (Filella *et al.*, 2004; Gamon *et al.*, 1995; Pettorelli *et al.*, 2005; Rundquist, 2002). In wetland landscapes, NDVI has been used to estimate aboveground biomass and productivity (Gross *et al.*, 1993; Hardisky et *al.*, 1984), assay wetland species distributions (Klemas *et al.*, 1993; Zhang *et al.*, 1997), and detect hurricane damage (Ramsey, Chappell, and Baldwin, 1997; Wang and D'Sa, 2010). Ramsey, Chappell, and Baldwin (1997) used NDVI to investigate damage in a forested wetland after the passage of Hurricane Andrew (1992) in Louisiana and found that changes mimicked damage and recovery patterns identified from posthurricane videography, and that abnormal phenologies could be clearly detected.

Although the relationship between NDVI and characteristics of

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wetland vegetation canopy has been established at the site level within primarily salt marsh communities, there are limited data relating spectral reflectance indices to field site measurements of cover, biomass, or productivity at landscape scales. Additionally, even fewer studies have linked NDVI to measurements of canopy structure in landscapes with multiple habitat types and in landscapes exposed to episodic stress. Penuelas *et al.* (1993) demonstrated that for a small lake in California, spectral reflectance characteristics could be distinguished between emergent, submerged, and floating aquatics, and that the NDVI values of the emergent aquatic plants were significantly correlated with biomass. Hope, Kimball, and Stow (1993) also found a relationship between aboveground biomass and NDVI in wet sedge tundra in Alaska and, along with Boelman *et al.* (2003), suggested that this relationship can be community specific. Wetland vegetation communities (habitat types) within coastal Louisiana have been well described and mapped according to major vegetation associations in 1949, 1968, 1978, 1988, 1997, 2001, and 2007 (Chabreck, 1972; O'Neil, 1949; Sasser *et al.*, 2008; Visser *et al.*, 1998, 2000, 2002), providing the opportunity to test if temporal trends in the NDVI vary by habitat type and if NDVI can be used to detect changes in conditions within habitat types after ecosystem disturbance.

Hurricanes Katrina and Rita

Louisiana's coastal wetlands experienced two Category 3 hurricanes within a 3-week period in late summer 2005 (Figure 1). Hurricane Katrina struck eastern Louisiana on August 29 with storm surge estimated between 3 and 6 m (Ebersole, Resio, and Westerink, 2007). Storm surge of Hurricane Rita exceeded 4 m at landfall in western Louisiana and eastern Texas on September 24 (McGee, Tollett, and Goree, 2007); with flooding effects identified across all regions of the coast (Doyle *et al.*, 2007). The storm surge brought in high salinity water, exposing forested wetlands and fresh, intermediate, and brackish marshes to salinities above typical ranges (Doyle *et al.*, 2007; Steyer *et al.*, 2007). Additionally, portions of western Louisiana were subjected to persistent surge-induced flooding from October 2005 through April 2006 based on satellite image analysis (Barras, 2006, 2007a, 2007b). The waves and surge also contributed to shear, a substantial physical disturbance where marsh vegetation was either partially or completely removed. These shears were detected in Landsat Thematic Mapper (TM) imagery as persistent, new open water bodies (Barras, 2006, 2007a, 2007b).

In this study we investigate a method that combines the use of field data (vegetation cover) with wetland change and vegetation index data to evaluate impacts to and recovery of several habitat types in coastal Louisiana after Hurricanes Katrina and Rita. We explore the extent to which impacts are due to physical disturbance or other physicochemical factors, how the effects varied by habitat type and region, and whether the effects were persistent. Additionally, we investigate the relationship between coarse resolution (250 m NDVI), moderate resolution (30 m TM), and fine resolution (4 m^2 cover plots) datasets and their utility in interpreting disturbance patterns.

METHODS

Study Area

The study area covers coastal Louisiana, with boundaries consistent with the Louisiana Coastal Area (LCA) trend assessment boundary (Barras *et al.*, 2003; Figure 1). This 33,457.6 km^2 complex of wetlands and open water extends from

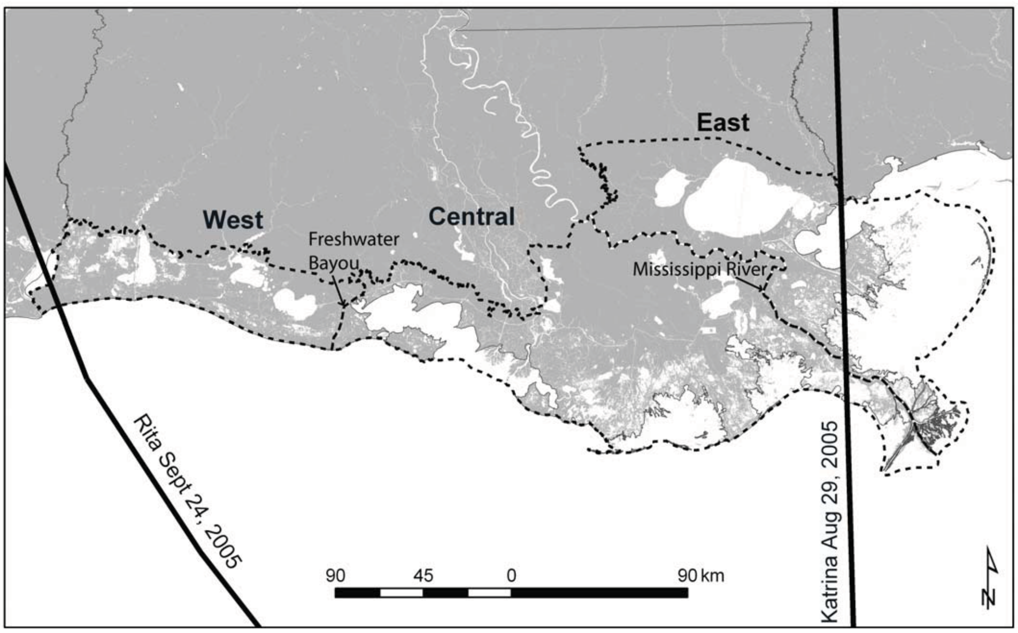

Figure 1. The location of the study area showing land/water area, regional assessment areas, and hurricane tracks.

the Texas–Louisiana line to the Louisiana–Mississippi border and encompasses habitat types from swamps and freshwater marshes in the north to salt marshes and barrier islands adjacent to the Gulf of Mexico in the south. For the purpose of this study, fastlands (*i.e.*, lands surrounded by levees that are generally excluded from consideration as wetlands) and other developed and agricultural lands were excluded from analysis. These exclusions leave a 2004 wetland base of 14,312.3 km^2 for the NDVI analyses (Barras, 2006).

Three regions within the study area were delineated to assess the direct effects of Hurricane Katrina (east) and Hurricane Rita (west) as well as the indirect effects (central) of both hurricanes (Figure 1). The Mississippi River is the boundary between the east and central regions and Freshwater Bayou is the boundary between the central and west regions. Regional landscapes exposed to hurricane landfall combined with a minimum 2-m storm surge were used to delineate regions directly impacted. Indirect hurricane effects included exposure to tropical force winds and flooding in some locations within the regional landscape.

Vegetation Index Imagery

Vegetation indices (VIs) derived from MODIS imagery provide temporally consistent data (16-day composites) at a spatial resolution of 250 m. Because this combination of temporal and spatial resolution is often considered ideal for regional-scale assessment of vegetation, MODIS 16-day composite VIs were chosen as the data sources for this assessment. The NDVI is a ratio that exploits varying absorption and reflection characteristics of red and near infrared (NIR) wavelengths of light. Reflections of red wavelengths of light decrease as chlorophyll in healthy, photosynthetically active leaves absorb this energy. In contrast, reflection of NIR wavelengths increases with increasing vegetative vigor and biomass. The NDVI formula [NDVI=(Xnir - Xred)/(Xnir + Xred)] results in a theoretical range from -1 to +1. A highly negative NDVI value typically denotes water or an absence of green vegetation, an NDVI value close to zero denotes no green vegetation, and an index value approaching +1 indicates high density of vigorous vegetation.

MODIS VI products are provided based on the Integerized Sinusoidal Grid. Tiles are identified on the basis of horizontal and vertical grid IDs. Atmospheric correction algorithms are used on the original spectral bands prior to VI computation; however, some residual aerosol and atmospheric contamination may persist in the NDVI product (Huete, Justice, and van Leeuwen, 1999). Further details describing the MODIS VI product preprocessing, compositing, and quality assessment can be found in Huete, Justice, and van Leeuwen (1999). Imagery was collected for the period of February 18, 2000–March 5, 2005, to create baseline monthly average NDVI composites. Imagery from March 6, 2005–December 3, 2006, was used to create monthly average NDVI composites for hurricane year evaluations. In total, 468 tiles were used to create the baseline composites, and 156 tiles were used to create the hurricane evaluation composites. Individual tiles were resampled and projected to Albers equal-area conic projection for North America.

The first step in examining the effects to the vegetative community was to establish a baseline for comparison. Comparing post-hurricane imagery on a monthly basis minimizes variability caused by senescence periods and other intra-annual variations, facilitating the isolation of hurricane impacts. The daily return frequency of MODIS enables creation of these temporally variable baselines, providing increased value over similar studies which have utilized sensors with coarse temporal resolution such as Landsat TM (Rodgers, Murrah, and Cooke, 2009) and studies that are dependent upon selection of discrete dates of pre- and post-hurricane imagery (Wang and D'Sa, 2010), that may represent abnormal patterns due to other phenomena.

Before monthly composites were created, the 16-day composites were subjected to further quality assessment and quality control (QAQC) masks, cloud recognition, and abnormality exclusion algorithms. Though the original MODIS algorithms for maximum value compositing (MVC) produces relatively cloud-free images, persistent cloud cover or aerosol contamination can lead to pixels that are contaminated or of unreliable quality in the final 16-day composite. Therefore, a secondary compositing methodology was employed to exclude these values from the average composites.

Those pixels with QAQC values representing "produced but with unreliable quality," "produced but contaminated with clouds," or "not produced because of bad quality" were recoded to a null value and excluded from consideration in the monthly averaging algorithm. For the baseline composites, the recoded images for that month were then inserted into an algorithm that further excluded contaminated or abnormal pixels whose values were missed by the original preprocessing algorithms. For each pixel in the image, this processing step calculated the standard deviation of the included pixels for a given month, then recoded and excluded pixels whose values were 1.5 standard deviations greater than or less than the mean. Pixels surviving the rigorous QAQC process were then summed and divided by the count of included pixels to form the final baseline composites.

Monthly baseline averages were typically created from 10 to 14 imagery composites collected during 16-day intervals. Hurricane year monthly averages typically included only two composites, so only the initial exclusion based on the QAQC flags was used. In the event that both pixels for a given month were flagged as "unreliable quality," the pixel was recoded to a null value. No further inferences can be drawn when comparing these pixels to their baseline monthly average. Pixels with a hurricane year composite value were then compared to the corresponding baseline composite to create a departure from average dataset (NDVI departure).

The NDVI departure datasets were used to classify the extent and severity of hurricane impacts into one of three classes defined for this study: (1) anomaly, identified as below or above average NDVI departure values; (2) significant damage, identified as an excess of one standard deviation lower than the baseline average NDVI value; and (3) persistent damage, identified as an excess of one standard deviation lower than the baseline average NDVI values during 12 out of the 14 months after a hurricane event.

Supporting Datasets

Identification of regional hurricane impacts was conducted by Barras (2006), who obtained and interpreted Landsat TM imagery using ERDAS IMAGINE® software to identify new water bodies appearing soon after hurricane landfalls. Standard methodology was used to classify land/water conditions and identify changes between 2004 and 2005 (Barras *et al.*, 2003; Morton *et al.*, 2005). The land/water classification used pre-hurricane images acquired between October 13 and November 7, 2004, and posthurricane images acquired between October 16 and October 25, 2005. The same methodologies were used in creating a 2006 land/water dataset from imagery acquired on October 28, 2006 (Barras, Bernier, and Morton, 2008). New open water areas in 2005 that remain classified as open water in 2006 were classified as persistent new water areas. Classification of persistent new water included areas with physical scouring of marsh and removal of land as well as persistent flooding. The classification of persistent new water areas between 2004 and 2006 was used as a mask to identify areas of persistent damage in the NDVI values that were attributed to physicochemical stressors (*e.g.*, salinity).

To monitor changes in vegetation, measurements of vegetation cover, species composition, and relative abundance were carried out between October 12 and November 1, 2005, and remeasured between September 6 and October 3, 2006, at 130 historical monitoring stations (4 m^2) located within the impact zone of Hurricanes Katrina (east region) and Rita (west region). These stations were randomly established under the Coastwide Reference Monitoring System (Steyer *et al.*, 2003), and measured using the Braun-Blanquet method described in Steyer *et al.* (1995). To assess vegetation recovery, 102 new stations were established after the hurricanes to measure the same vegetation variables that were sampled across coastal Louisiana in 2006, in spring (March 23–29), summer (July 7–11), and fall (October 28–November 3) in order to assess vegetation recovery. Calculations of NDVI values from 250-m pixels corresponding to these vegetation stations were directly compared on a station-by-station basis. Changes in cover between 2 time periods were compared with changes in NDVI values from the same time periods.

Trying to correlate remotely sensed data of relatively low spatial resolution with fine-scale, ground-based vegetative sampling has inherent problems (Fairbanks and McGwire, 2004; Gould, 2000; Rocchini, 2007), especially in heterogeneous and fragmented environments such as the coastal ecosystems of south Louisiana. These complications and the assumptions necessary for using the plot data were, however, considered reasonable in the present study, where the objective was not absolute accuracy but a relative evaluation of vegetation response and recovery.

RESULTS

NDVI Baseline Data (2000–2005)

The monthly baseline NDVI values for predominant habitat types in coastal Louisiana by study area region illustrate the influence of season, growth phenology, plant morphology, and landscape fragmentation on NDVI (Figure 2). The temporal profile clearly illustrates the growing season in coastal Louisiana with increasing NDVI values in March and April associated with

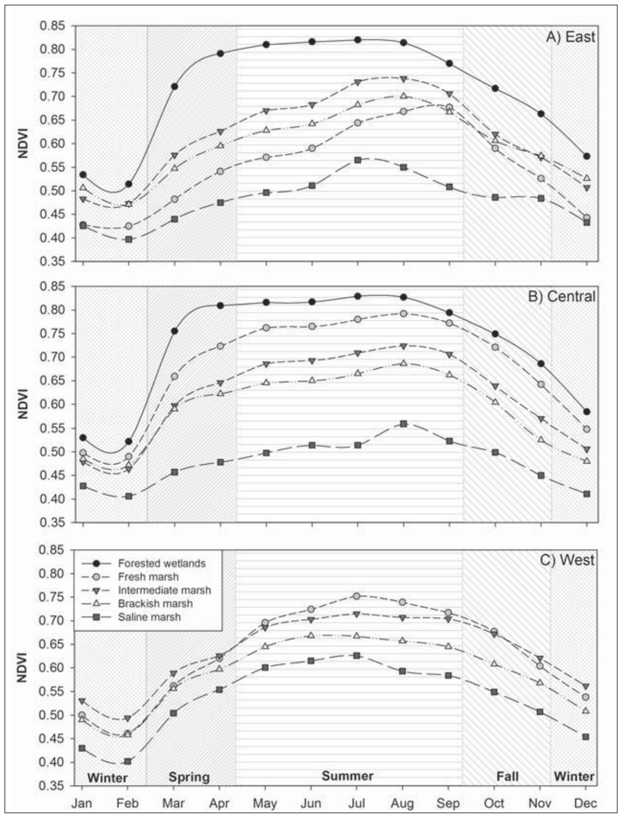

Figure 2. Seasonal trends of mean values in the Normalized Difference Vegetation Index (NDVI) by habitat type and regions within coastal Louisiana: (A) east, (B) central, and (C) west. The mean NDVI value is a monthly average composite derived from MODIS imagery collected for the period of February 18, 2000–March 5, 2005, and serves as the baseline value in the study.

spring green-up, highest NDVI values in summer, and lowest values in October through February associated with winter senescence of emergent vegetation and forest leaf-off conditions. The NDVI summarized by habitat types showed lowest values in saline marsh followed by brackish marsh < intermediate marsh < fresh marsh < forested wetland. The fresh marsh in the east was the only deviation in this pattern and may be attributed to (1) fresh marsh comprising less than 1% of the vegetated landscape in this region, and (2) high percentages of water found in this fresh marsh zone. The NDVI values by habitat type are also consistent with the extent of open-water area within each zone.

Departure Patterns and Trends in NDVI Values

The monthly time series showing anomalous departures from average NDVI values illustrate effects of Hurricane Katrina in September 2005 and the combined effects of Hurricanes Katrina and Rita after September 2005 (Figure 3). At a regional scale, immediate departures from average suggest that Hurricane Katrina substantially reduced vegetation conditions in the east with minimal influence in the other regions; whereas Hurricane

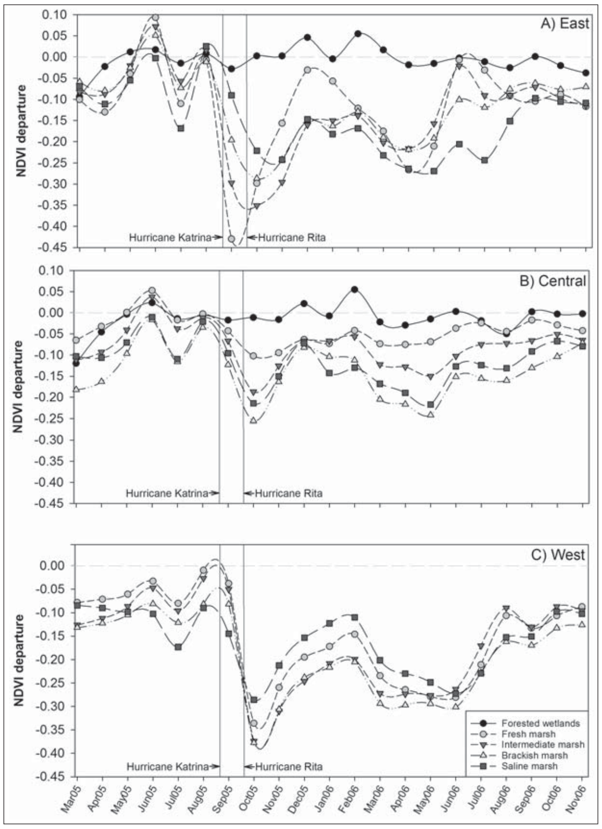

Figure 3. Time series of departure from average values using Normalized Difference Vegetation Index (NDVI) by habitat type beginning in March 2005 and ending in November 2006 for (A) east, (B) central, and (C) west regions. Habitat types are indicated in the key of panel (C). The vertical lines represent landfall dates of Hurricanes Katrina and Rita. A departure value is calculated by subtracting monthly average NDVI composites for the hurricane year from baseline NDVI values. The horizontal dashed line illustrates no difference in values between months investigated and baseline averages.

Rita immediately influenced all regions. Departure values for emergent marshes after the hurricanes generally show positive trends through the winter, negative trends through midsummer, and positive trends from late summer to fall. The positive trend in the winter is misleading since smaller departures would normally be expected between baseline and posthurricane winter months from naturally occurring vegetation senescence. Departure values in the forested wetlands show minimal variation throughout the study period, with a typical departure of less than -0.03 immediately after the storms. Forested wetlands were also the only habitat type where substantial above average departures occurred (in December 2005 and February 2006).

In the east region, fresh and intermediate marsh suffered the most dramatic and immediate impacts of Hurricane Katrina, with mean departure values of -0.43 and -0.30, respectively, in September 2005 (Figure 3A). Fresh marsh, however, rapidly improved by December 2005 with a departure value of -0.031, before a declining trend occurred through the early summer. A second strong recovery occurred between May and June 2006 when NDVI values reached prehurricane baseline values. Intermediate, brackish, and saline marshes had similar below average departure curves throughout the posthurricane time period except during June and July, the period of peak vegetation biomass, when below average salt marsh departures were much greater than in the other marsh types.

The central region experienced the smallest departure from average, with mean departure values never exceeding -0.26 across all habitat types during the posthurricane time period (Figure 3B). Brackish and salt marsh zones had the greatest below average departures, showing gradual improvement along with intermediate marshes from May 2006 until November 2006. Fresh marsh experienced the least variability and had the smallest departures from average of all marsh types in this region.

The impacts in the west region were apparent in October 2005 after Hurricane Rita. All marsh types had mean departure values exceeding -0.28 in October 2005 and again in June 2006 (Figure 3C). The departure trends and variability among marsh types in the west region were very similar, with the brackish marsh zone having the greatest departures. Positive trends in vegetation conditions occurred in all marsh types beginning in July 2006, with the greatest recovery in fresh marsh between July and August 2006.

Spatial anomaly patterns in the NDVI values for coastal Louisiana are shown in Figure 4. A substantial decline in vegetation density and vigor was observed across the east region from August 2005 to September 2005 after Hurricane Katrina (Figures 4A and 4B) and was prevalent across all regions from September 2005 to October 2005 after Hurricane Rita (Figures 4B and 4C). The color ramp depicts increasing severity of departure from average NDVI values across the coast, with dark green and red illustrating largest departures. The greatest anomalies are located in the direct hurricane impact areas. A conspicuous feature of these data is the large spatial extent of the Hurricane Rita impact, encompassing both direct and indirect areas.

Departure patterns in the NDVI values suggest that over 4,714 km^2 or 32.9% of the prestorm coastal wetland area of Louisiana experienced an immediate and significant decline in vegetation density and vigor in October 2005. The largest area of vegetation decline was in the west region with 2,400 km^2, followed by the central region with 1,268 km^2, and east region with 1,046 km^2 (Figure 4C). These effects occurred over 67.6% of the prestorm west coastal landscape area, 15.5% of the central region, and 30.4% of the east region. Above average NDVI values (green color ramp) became conspicuous across broader landscapes in June 2006 in the east and central regions (Figure 4D). The majority of the coast remained at below average NDVI values in October 2006, one full growing season after the hurricanes, with significant departures from average NDVI values (Figure 4E); however, all regions of the coast showed some recovery in vegetation conditions towards the end of the first growing season.

NDVI Values for Significant and Persistent Damage

The departure anomalies in the NDVI for hurricane year evaluations account for all factors influencing the vegetated landscape over the time period. To better isolate the effects of the hurricanes, significant damage was calculated as an excess of one

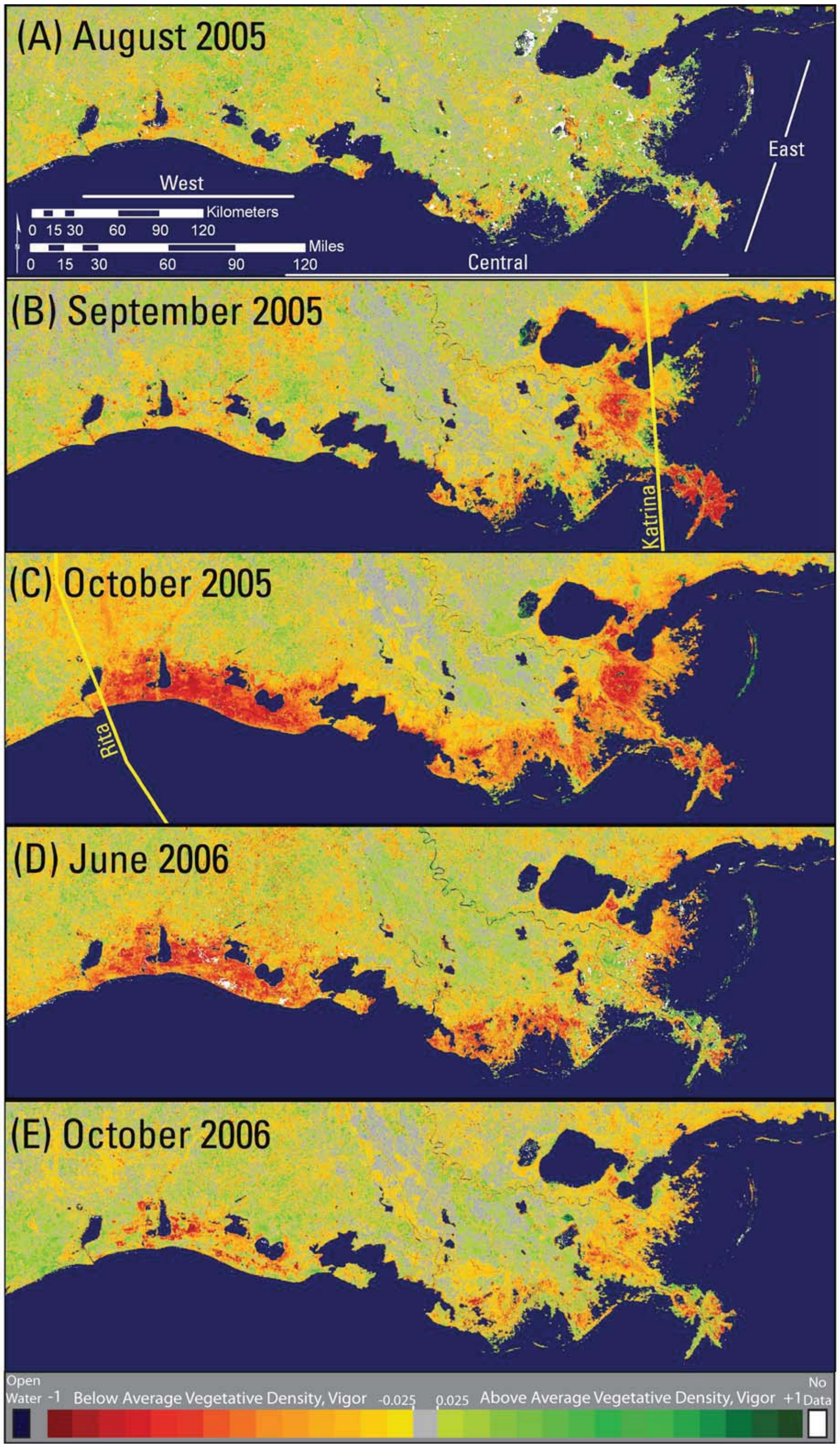

Figure 4. Departure from average patterns using the Normalized Difference Vegetation Index (NDVI) for the study area from August 2005 (before Hurricanes Katrina and Rita), September 2005 (immediately after Hurricane Katrina), October 2005 (immediately after Hurricane Rita), June 2006, and October 2006 (one year after Hurricane Rita). Red and green color ramps represent below average and above average vegetation density and vigor, respectively.

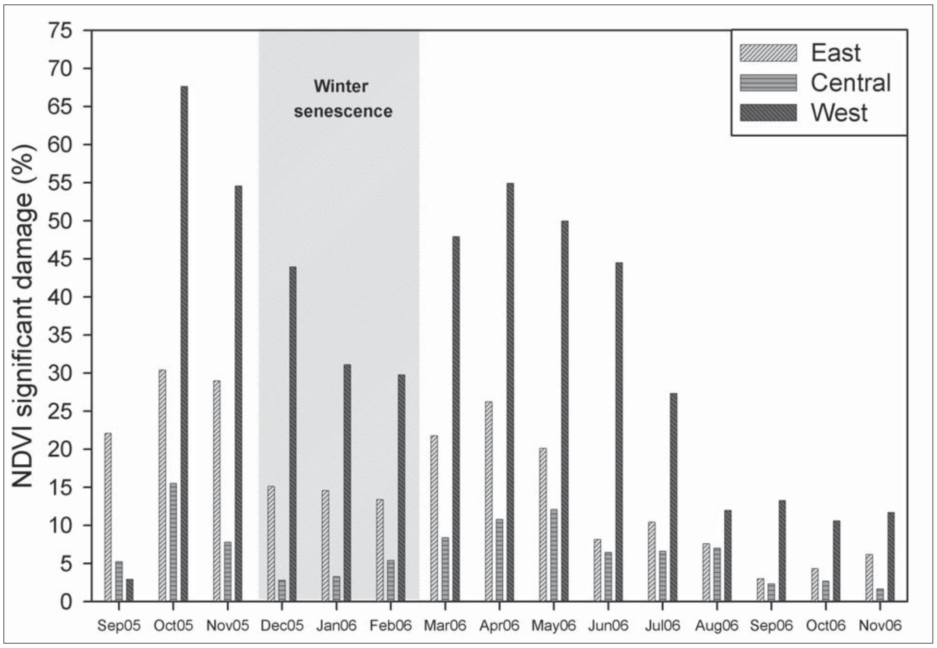

Figure 5. Seasonal trends of significant damage (normalized difference vegetation index [NDVI]) being more than one standard deviation lower than the baseline average) in the east, central, and west regions by percentage of area following Hurricane Katrina, beginning in September 2005 and ending in November 2006. The shaded months represent the winter season when emergent marsh vegetation senescence and forested wetland leaf-off conditions occur.

standard deviation lower than the baseline average NDVI values. If significant damage occurred in 12 of the 14 months following a hurricane event, the damage was considered persistent. There was significant damage in 22% of the east region in September 2005 after Hurricane Katrina, with an increase to 31% in October 2005 after Hurricane Rita (Figure 5). The percent of landscape significantly damaged after Hurricane Rita in September 2005 increased by 10.3% in the central region and 64.8% in the west region. Excluding winter senescence, significant damage remained in over 20% of the east region through May 2006 and over 45% of the west region through June 2006; however, significant damage never exceeded 16% of the landscape in the central region (Figure 5).

Persistent damage occurred in 192.4 km^2 (5.6%) of the east, 89.4 km^2 (1.1%) of the central, and 1045.6 km^2 (29.5%) of the west region by November 2006 (Figure 6A). Though there appears to be an inconsistency among the percentage of the landscape persistently damaged in Figure 6A and the monthly significant damage displayed for November 2006 in Figure 5, the difference in definition of these two terms explains the pattern. The west region in particular displays a smaller percentage of monthly significant damage from August to November of 2006 than is defined as persistent damage. This pattern suggests that many pixels in the west region met the persistent damage criteria in 12 of the earliest months after the hurricane. This pattern may also suggest variability in how pixels pass or fail the standard deviation criteria for significant damage from month to month.

The habitats where the most persistent damage occurred were in intermediate marsh in the east, brackish marsh in the central, and fresh and intermediate marshes in the west regions (Figure 6B). Fresh and intermediate marsh communities made up 56.3% of the persistent damage in the east region, 27.5% in the central, and 77.1% in the west region.

Relationships Among Multitemporal NDVI Values, Land Change, and Vegetation Change

The localized persistence of severe, below-average departures (Figures 4 and 6) suggests that the creation of new water area by physical disturbance and persistent flooding may be an important causal factor. The persistence of new open water was classified by Barras, Bernier, and Morton (2008) as the 2004–2006 changes in open water that persisted for at least one year after the 2005 hurricanes. The persistent new water area was 527 km^2, which occurred over 5.3% of the total 2004 wetland area represented in the east region, 0.9% in the central region, and 8.4% in the west region (Figure 6A). The percentage of area of persistent damage accounted for by new open water in the east, central, and west regions is 91.8%, 81.0%, and 29.0%, respectively (Figure 6A).

The persistent new water area was most prevalent in the intermediate marsh in the east region, and fresh marsh in the central and west regions (Figure 6C). The allocations of persistent damage and persistent open water by habitat type were nearly identical in the east; however, they were quite different in the central and west regions. Persistent new water area was dominant in fresh marsh in the central region at 80% and 78% in the west region; whereas, persistent damage in the fresh marsh was only

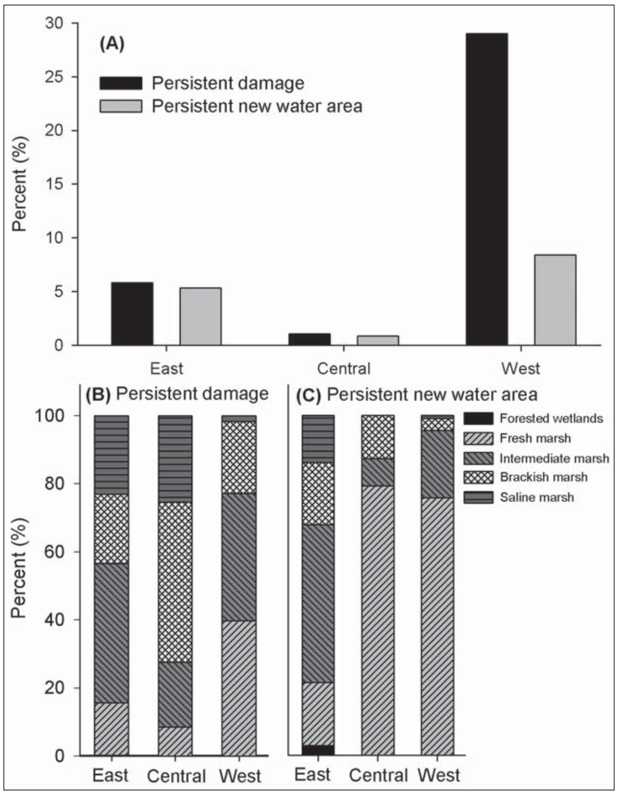

Figure 6. (A) The percentage of landscape area in the east, central, and west regions with persistent damage through November 2006. (B) The allocation of persistent damage by habitat type in the east, central, and west regions. Habitat types, as described in part (C), are based on Chabreck (1972) classifications. If significant damage (normalized difference vegetation index [NDVI]) being more than one standard deviation lower than the baseline average) occurred in 12 of the 14 months following a hurricane event, the damage was considered persistent. (C) The allocation of persistent new water area by habitat type.

9% in the central and 40% in the west region. Additionally, in the central region we identified no persistent new water area in salt marsh; however, we identified nearly 21% of persistent damage in salt marsh.

Measurements of vegetation cover from field data were used to assess the spectral values in the NDVI and to ground truth vegetation recovery. The relationship between changes in NDVI values and changes in total live cover (when all potential time periods from both quarterly and annual sampling were included) produced an r^2 of 0.38 ($P < 0.0001$; $n = 287$; Figure 7). Increases in NDVI change values over time generally corresponded with increases in total live cover, but the fit for this relationship was not very strong. The field data also helped corroborate spectral values from June 2006 in the east region (Figure 4). The above-average density and vigor in summer appears to be associated with colonization by annual plant species (Figure 8). The low cover values in the west throughout 2006 are consistent with classifications of persistent damage in the NDVI.

DISCUSSION

The mean monthly NDVI values from the 5-year baseline time series (Figure 2) clearly follow seasonal patterns that are consistent with growing degree day classifications for this region (U.S. Department of Agriculture, 1995) and seasonal temperature reported by the Southern Regional Climate Center (2008). Seasonal trends shown in the NDVI have never been investigated across different wetland types and reported in the literature; however, the seasonal trends appear to be consistent with previous aboveground biomass studies in Louisiana that generally show increases in live, aboveground biomass from low values in the winter to peak values in summer (Conner and Day, 1976; Hopkinson, Gosselink, and Parrondo, 1978; Sasser and Gosselink, 1984; White *et al.*, 1978). Seasonal trends reported by Zhao *et al.* (2009) for salt marsh in the Yangtze River Delta were comparable with our salt marsh results. Our study identified a clear differentiation among NDVI values by habitat type, suggesting that the NDVI is sensitive to phenology changes. The higher NDVI values in fresh marsh may be associated with the higher reflectance from broad-leaved plants, which Hardisky, Gross, and Klemas (1986) identified as having higher vegetation index scores as compared to gramineous and leafless plant canopies. Chabreck (1972) documented the greatest abundance of broad-leaved plants in fresh marsh and graminoids in brackish and salt marsh in coastal Louisiana. Landscape fragmentation patterns may also explain the higher NDVI values in fresh marsh. Barras (2006) identified the amount of land and water by 2001 marsh community type and found the greatest percentage of water in saline and brackish marsh and the highest percentage of contiguous vegetated landscapes in intermediate and fresh marsh. Within California salt marshes, Zhang *et al.* (1997) tested six spectral vegetation indices including NDVI and found that all provided reasonable estimates of biomass, regardless of species composition and specific site conditions, and that most indices provided relative trends consistent with edaphic gradients. Louisiana habitat classifications have broadly followed a gradient of salinity zones from the Gulf of Mexico (Chabreck, 1972; O'Neil, 1949; Penfound and Hathaway, 1938), further suggesting the use of spectral signatures in evaluating habitat change.

Forested wetlands experienced a slight decline in vegetative density and vigor immediately after Hurricane Katrina; however, unlike other marsh communities, they appeared to recover readily. Aerial reconnaissance and ground surveillance confirmed the sprouting of new green leaves 5–7 weeks after the hurricanes in forested wetlands within the Pearl River basin in east Louisiana (Barras, 2007b; Barrow *et al.*, 2007). The above-average departure from NDVI values in December 2005 appears to be the result of an abnormal bloom of new leaves after defoliation and/or an increase in midstory vegetation capitalizing on new openings in forest canopy, which is consistent with findings from Ramsey, Chappell, and Baldwin (1997) and Doyle *et al.* (1995) after Hurricane Andrew in 1992.

The monthly anomaly patterns in NDVI values in nonforested marsh communities clearly showed the effects of Hurricanes Katrina and Rita, both spatially and temporally. Hurricane Katrina's impacts were primarily located in the east region, where nearly 91.8% of persistent damage was accounted for

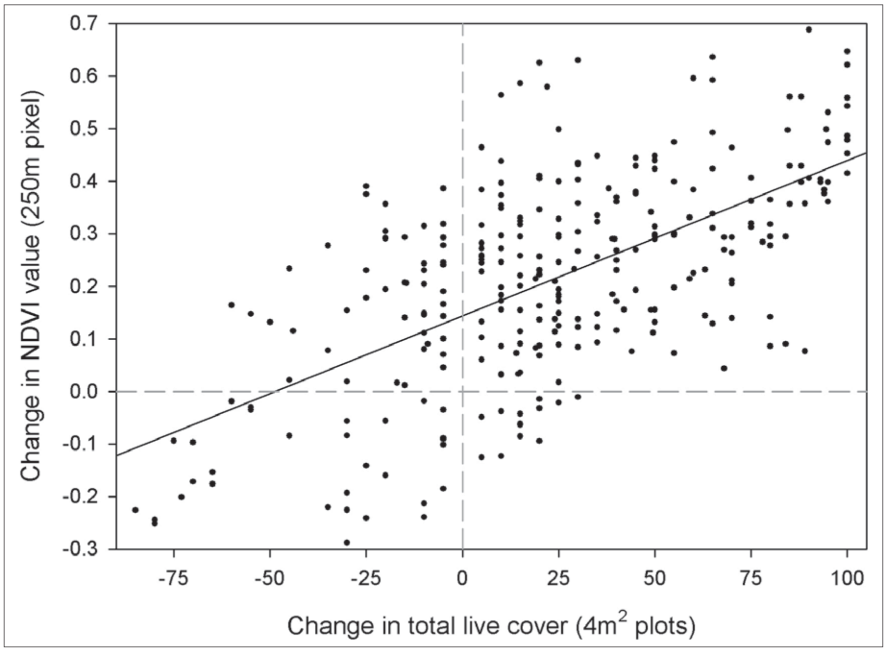

Figure 7. The relationship between change in NDVI value at 250-m pixels and change in total live cover at 4-m^2 plots for each time period at stations across coastal Louisiana. Time periods used to calculate change are fall 05–fall 06, spring 06–summer 06, and summer 06–fall 06. Change in NDVI value=0.1439 + 0.0030 percent change in total live cover, with r^2 =0.38.

by formations of new water area (Figure 6A). The damage affected all marsh types and was formed primarily from physical scouring and the direct removal of land as described in Barras (2006). The above-average values in the NDVI in fresh and intermediate marshes within the upper east region in June 2006 (Figure 4D) appear to be associated with a significant increase in the number and relative cover of annuals and disturbance plant species identified from field sampling between late March and early July 2006 (Steyer *et al.*, 2010). The use of field monitoring stations to identify changes in species composition, which can be difficult to distinguish using remotely sensed data, can improve interpretations of recovery.

The impacts associated with Hurricane Rita were much greater in spatial extent and more persistent than Hurricane Katrina. The departures from average NDVI values after Hurricane Rita correspond well with the east to west increase in physical shearing and flooding observed by Barras (2007a, 2007b); however, physical removal of marsh and flooding could not solely explain the patterns observed in the west. Only 29% of the persistent damage in the west, which was identified by using departures from average, was associated with new water area. If conversion to new open water is the primary contributing factor in departure trends, damage within each marsh type should be reflected in the patterns of conversion to new water area, but such was not the case in the central and west regions. Though an overwhelming majority of the conversion to new water area in these regions occurred in fresh marsh, damage in all three regions was spread among all of the marsh vegetation types. The extent of persistent damage in the west and the pattern of persistent damage across all vegetation types are consistent with Hurricane Katrina and Rita results from Piazza *et al*. (2011). Piazza *et al*. (2011) found significantly lower live aboveground biomass in fresh marsh in the west region and primarily attributed vegetation impacts to elevated porewater salinities in the west and central regions and physical disturbance in the east region. The physicochemical disturbances in the west and physical disturbances in the east were detected through field observations and their results assisted us in verifying patterns observed in the remotely sensed imagery.

The ability to integrate geographic information systems and remote sensing by using multisource and multitemporal imagery is an important method for change detection (Lu *et al.*, 2004; Petit and Lambin, 2001). We also found that field data augmented our ability to discern landscape changes at regional scales. Although the relationship we derived between vegetation data collected at 4 m^2 with 250-m NDVI was not robust, a multitude of factors including varying resolution and interspersion of land and water may explain this finding. Rogan *et al.* (2011) found strong correspondence among field plots and forest damage using Enhanced Vegetation Index (EVI) data from MODIS when both datasets were recorded at the same scale (250 m). In this study, it was not our intent to use NDVI as a predictor of vegetation cover or to aggregate data layers to match scales.

The use of anomalous NDVI values and departures from average for greenness has been commonly used for the evaluation of drought and rainfall effects on vegetation dynamics and fire potential (Anyamba and Tucker, 2005; Burgan, 1996;

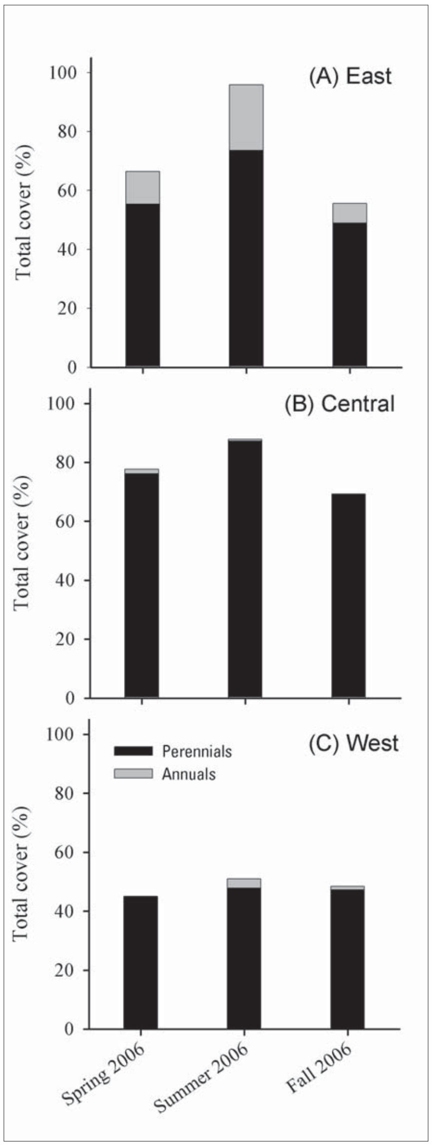

Figure 8. Percent cover of perennials and annuals in (A) east, (B) central, and (C) west regions across all seasons in 2006.

Burgan, Hartford, and Eidenshink, 1996; Nicholson, Davenport, and Malo, 1990). Departures from average provided us a good indication of the extent and severity of initial hurricane effects and persistence over time across habitat types. It accurately detected that a change occurred and identified the spatial extent and pattern of change over time, which are of fundamental importance in change detection applications (MacLeod and Congalton, 1998). Kearney and Riter (2011) suggest that large departures in vegetation vigor in Delaware Bay marshes in 2004 were associated with impacts from Hurricane Isabel. Similarly, the severe changes in index values after Hurricanes Katrina and Rita overwhelmed minor changes that could have been caused by other factors such as atmospheric conditions, sun angles, and soil moisture levels that may not have been captured by correction algorithms, thus providing confidence in our ability to detect response and recovery with this approach. There is still a need to examine the performance of different spectral indices in coastal wetland community types by testing the influence of factors such as sun position, heterogeneous landscape, or atmospheric interferences. Blackburn and Steele (1999) found that the relationship between reflectance and biophysical canopy properties varies depending on the heterogeneous structure of different community types. Testing and verifying these relationships would provide a robust method for evaluating ecosystem functioning at complex landscape scales (Filella *et al.*, 2004).

CONCLUSIONS

The most evident value of the current research was quantifying the impacts of the 2005 hurricanes on the marshes of coastal Louisiana across regional landscapes. Land change patterns as classified from TM imagery, in conjunction with the NDVI change detection obtained through MODIS imagery, improved our ability to detect change and dissect causal mechanisms of that change. The 30-m spatial resolution of the TM data and the temporal consistency of the 250-m MODIS imagery enhanced interpretation ability beyond that of either sensor examined alone. The power of using moderate to coarse resolution TM and MODIS imagery is that the entire spatial extent of impacts from Hurricanes Katrina and Rita could be captured rather than interpolated from regional or site-specific investigations. The departures from average NDVI values clearly illustrate how differing hurricane tracks and associated storm surges impact the coastal wetlands, and that Hurricane Rita's effects were more persistent and affected a much larger spatial extent than Hurricane Katrina. Hurricane Katrina's track was northerly, isolating storm surge and associated surge-induced marsh removal primarily to the east region (Barras, 2007a; Ebersole, Resio, and Westerink, 2007). Hurricane Rita's track was northwesterly and subjected the central and west regions to sustained tropical force winds and elevated water levels in advance of landfall (Lockwood, 2005) and storm surges in all regions upon landfall (Doyle *et al.*, 2007; McGee, Tollett, and Goree, 2007). The storm surge also amplified impacts in the west region when water became impounded behind artificial levees and water control structures and became impounded naturally when existing canals and waterways were completely filled with wrack and storm debris (Michot, Wells, and Chadwick, 2007). These persistently flooded landscapes made it difficult to classify whether new water area was caused by physical disturbance or resulted from other factors. It has been suggested that the persistence of high salinity conditions after widespread flooding of low salinity marshes has contributed to vegetation damage in the west (Piazza *et al.,* 2011; Steyer *et al.*, 2007). Comprehensive field monitoring networks that examine the influence of major stressors (*e.g.*, salinity and flooding) on vegetation community dynamics are underway, and when combined with multitemporal vegetation indices, should further elucidate physical from physicochemical impacts and assist in identifying recommendations for restoration and management actions.

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