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The Resilience Of Coastal Marshes To Hurricanes: The Potential Impact Of Excess Nutrients

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The resilience of coastal marshes to hurricanes: The potential impact of excess nutrients

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ABSTRACT

Hurricanes pose an increasing threat to coastal environments as the intensity and severity of hurricanes are predicted to increase under the changing climate. Coastal wetlands are effective nature-based defenses of coastal cities against storms. However, the ecosystems themselves are also susceptible to the impacts of hurricanes, which are highly complex and not fully understood. Here we utilize multi-decadal satellite data archives (Landsat 1984–2014 and MODIS 2005–2015) and long-term coast-wide field-based environmental data (1978–2018) to investigate the impacts of hurricanes Katrina (2005), Gustav (2008), and Isaac (2012) on the coastal marshes in Louisiana, USA, where the hurricanes made landfall. While the hurricanes had immediate impacts on the marshes' biomass and area at an ecosystem scale, general recovery was observed in the next one and two years. We also found that the most severe damage always occurred in the intermediate and brackish marshes of the Breton Sound basin, where the nitrogen concentration in the water was significantly higher compared to areas with less damage ($P < 0.01$). Because excess nutrient can reduce the marshes' root growth and degrade their root mat, we posit that the long-term nutrient enrichment in the area, which resulted from the diverted Mississippi River water, has increased the marshes' susceptibility to hurricanes. The results highlight the resilience of coastal marsh ecosystems against hurricanes, but also underline the profound synergistic effects of climatic and anthropogenic factors on the sustainability of coastal ecosystems, which have important implications for coastal management under the current climate trend.

1. Introduction

Over 40% of the world's population lives within 100 km of the coastline and the world's coastal urban population doubled from 45 to 88 million people in the last 40 years (Martínez et al., 2007; Pesaresi et al., 2016). Coastal areas, however, face increasing threats from storms under climate change. The globally averaged storm intensity is expected to increase by 2–11% by 2100 due to greenhouse warming, and the storm surges are likely to increase with the rising sea-level (Knutson et al., 2010; Smith et al., 2010; Reidmiller et al., 2018). Coastal wetlands—besides their ecological services such as food provision, water quality improvement, biodiversity conservation, and carbon sequestration—are effective nature-based defenses of coastal cities against the effects of storms (Costanza et al., 2008; Wamsley et al., 2010; Zhang et al., 2012; Stark et al., 2015), and are potentially more sustainable and ecologically sound compared to conventional coastal engineering structures (Temmerman et al., 2013). However, coastal wetlands themselves are also susceptible to the impacts of storm hazards (Michener et al., 1997).

The Mississippi River delta is among the world's five largest river deltas (Bianchi and Allison, 2009; Ericson et al., 2006). The delta is comprised of a series of overlapping delta lobes resulting from the different courses the Mississippi River has taken over the past 8000 years (Turner et al., 2017). The extensive coastal marsh ecosystem established in the delta comprises about 40% of coastal wetlands in the contiguous States, and provides economic and ecological benefits exceeding \$100 billion (Louisiana Office of Coastal Protection and Restoration; LCWCSTF, 1993; 2015; Williams, 1995; Barbier et al., 2013; Nahlik and Fennessy, 2016; U.S. Geological Survey, 1996). Yet, the marshes and their valuable functions are under increasing stress from hurricanes arriving from the Gulf of Mexico as the storm surges increase with the rising sea-level in the area (Smith et al., 2010).

The impacts of hurricanes on coastal marshes are very complex, and contradictory results are often found in the literature. Hurricanes may damage marsh plants and reduce the biomass production that is necessary for organic accretion (Morton and Barras, 2011). Conversely,

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hurricanes can stimulate marsh root growth in the following years and increase marsh belowground biomass production (McKee and Cherry, 2009). The hurricane-induced storm surges may decrease marsh elevation by removing marsh substrates near the shoreline and channel edges through scouring and erosion (Barras, 2006) or, in contrast, increase marsh elevation by bringing in large amounts of sediment onto the flats (Turner et al., 2006; Tweel and Turner, 2014). In addition, the levels of impacts may vary among vegetation types and locations (Howes et al., 2010; Kearney et al., 2011).

Here, we conduct a long-term satellite and ground-based study to examine the impacts of three major hurricanes, i.e., Katrina in 2005, Gustav in 2008, and Isaac in 2012, on the coastal marshes of the northern Gulf of Mexico. We use multi-decadal remote sensing data archives (1984–2015) to study the spatial and temporal patterns of the hurricanes' impacts on the marshes' biomass and area, and use long-term coast-wide field-based environmental data (1978–2018) to investigate the environmental factors that may amplify the impacts. We hypothesize that hurricanes impact the marshes' biomass and area at an ecosystem-scale and that the level of impacts is a function of vegetation systems (i.e., tidal freshwater, intermediate, brackish, or saline marshes) and environmental factors. The results of this study will improve our understanding of the impacts of hurricanes on coastal ecosystems and have strong implications for coastal management coping with a changing climate.

2. Methods

2.1. Hurricane records and study area

This study inspected the effects of three major hurricanes in the Gulf of Mexico, i.e., Katrina in 2005, Gustav in 2008, and Isaac in 2012 (Fig. 1). Katrina passed over Louisiana as a Category 3 hurricane on August 29th, 2005 (Day of Year, or DOY, 241), Gustav as a Category 2 hurricane on September 1st, 2008 (DOY 245), and Isaac as a Category 1 hurricane on August 29th, 2012 (DOY 242; Historical Hurricane Tracks, National Oceanic and Atmospheric Administration, NOAA). This study focused on the marshes in southeastern Louisiana, where the hurricanes made landfall: the Terrebonne basin, the Barataria basin, the Birdfoot Delta, the Breton Sound basin, and the Pontchartrain basin. The coastal marshes in Louisiana are classified into freshwater, intermediate, brackish, and saline marshes based on vegetation associations and salinity. The marsh distributions were obtained from vegetative surveys from the closest year (Chabreck and Linscombe, 1978, 1988, 1997; Linscombe and Chabreck, 2001; Sasser et al., 2008; Sasser et al., 2014). It should be noted that there was another hurricane, Rita, made landfall at the Texas/Louisiana border in 2005 (Category 3; September 24th, DOY 267), whose path was southwest to the study area.

2.2. Satellite-based marsh biomass assessment

The Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices product, MOD13Q1v006 (Terra), was employed to study the marsh biomass change before and after hurricanes (Didan et al., 2015). The MOD13Q1 data are 16-day composites at a 250-m spatial resolution. In a composite, each pixel is filled with the best available value collected during the 16-day period, i.e., data acquired under low cloud cover and low view angle and had the highest vegetation index value (Didan et al., 2015). Pixels that don't have reliable data acquired during the acquisition windows—due to, for example, aerosols and cloud contaminants—are filled with historical NDVI averages. The high revisit-frequency of the MODIS satellites increase the chance of having high-quality pixel values for the composite image. The use of the 16-day composites reduces the impact of tidal variation in the analysis because the selection of highest vegetation index values favors data taken under low-tide conditions (Kearney et al., 2009).

The Normalized Difference Vegetation Index (NDVI) vegetation layer from the MOD13Q1—calculated from the surface reflectance (ρ) of the red and near-infrared (NIR) bands: NDVI = $(\rho_{NIR\ band} - \rho_{red\ band})/(\rho_{NIR\ band} + \rho_{red\ band})$—was used to infer the marsh biomass. NDVI is a unitless ratio ranging from −1 to 1. The correlation of determination (R^2) between NDVI and LAI of the marshes is 0.7 (Mo et al., 2018). Pixels with negative NDVI were considered as water bodies and filtered out. Because hurricanes Katrina, Gustav, and Isaac all passed over the study area between the end of August and the beginning of September, we examined the NDVI changes over the senescence period, i.e., the end of the growing season, between mid-August and early September (i.e., one week after the hurricanes) and between mid-August and late September (i.e., four weeks after the hurricanes) from 2004 to 2015. Three MOD13Q1 images were used in each year for a total of 36 datasets (Fig. A1). The NDVI change of each pixel between

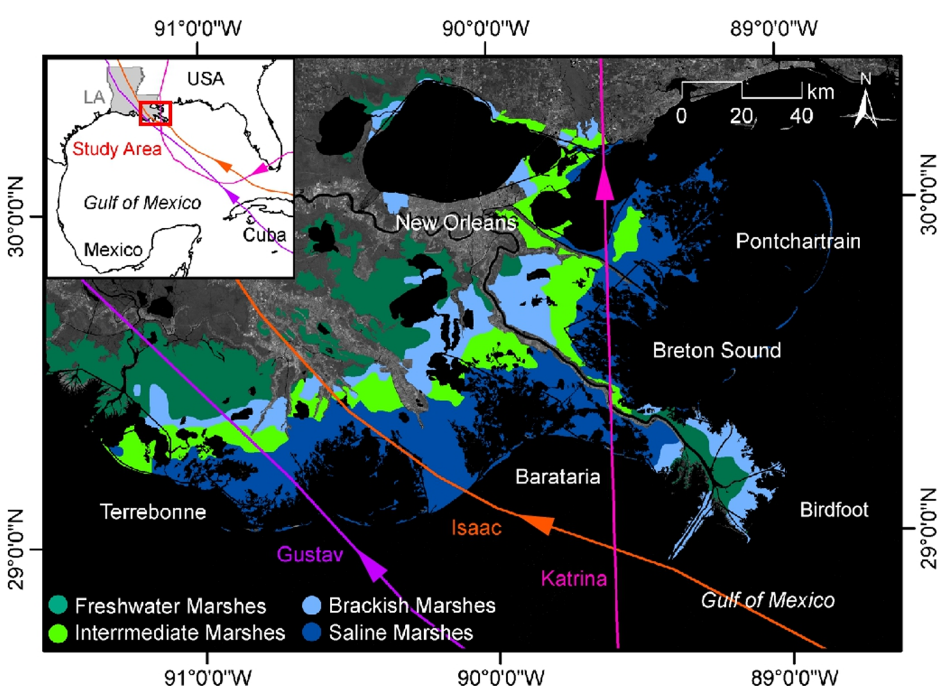

Fig. 1. The paths of hurricanes Katrina, Gustav, and Isaac in the Gulf of Mexico (indicated in *pink, purple,* and *orange lines*, respectively; Historical Hurricane Tracks, National Oceanic and Atmospheric Administration, NOAA) and the study area in southeastern Louisiana, USA: freshwater, intermediate, brackish, and saline marshes (*dark green, light blue, green, and blue areas*, respectively) in the Barataria basin, the Breton Sound basin, the Pontchartrain basin, the Terrebonne basin, and the Birdfoot Delta. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

two MOD13Q1 images was calculated as the % NDVI change = $(NDVI_{after} - NDVI_{before})/NDVI_{before}$. The % NDVI change is used to infer the relative biomass changes in each pixel, as the four marsh types have different annual peak NDVI (Mo et al., 2015; Mo et al., 2018).

2.3. Satellite-based marsh phenology assessment

The Landsat Climate Data Record (CDR) data were used to examine the hurricane impact on the marsh phenology, i.e., their annual growth pattern. The study area lies within the Landsat scenes of Path 22 Row 40 and Path 22 Row 39. The satellite imagery was collected by three Landsat series satellites: the Landsat 5 launched in 1984 and decommissioned in 2011, the Landsat 7 launched in 1999, and the Landsat 8 launched in 2013. All three satellites provide data with a 30-m spatial resolution and a 16-day revisit cycle. The long and continuous record since the 1980s allows us to examine multiple hurricane events for a better understanding of the general patterns of the impacts. The finer resolution of 30 m offers data with fewer mixed pixels (of land and water), and thus reduces the impact of mixed pixels occurring in the analysis as a source of error when estimating the marsh boundary/area.

During 1984–2014, we identified three hurricane years (2005, 2008, and 2012), three post-hurricane years (2006, 2009, and 2013), and four "normal" years that did not experience extreme weather events such as hurricane, drought, and flooding in the current and preceding years (1984, 1987, 1994, and 2014). Due to the limited relatively-cloudless images, we used only data from 2005 and 2008 to examine the phenology of the marshes in the hurricane years, and data from 2009 were used to investigate the post-hurricane phenology. There were 8, 12, 9, 24, 20, 19, and 22 relatively-cloudless images (mosaics of scenes Path 22 Row 40 and Path 22 Row 39) used for 1984, 1987, 1994, 2005, 2008, 2009, and 2014, respectively, for a total of 114 images (Fig. A1).

The Landsat CDR data in the selected years were subjected to phenological modeling. The NDVI was calculated for each pixel. The cloud, cloud shadow, and water pixels were filtered out using the C version of the Function Mask (CFMask; Zhu and Woodcock, 2012), and so the subsequent analysis was limited to the NDVI of land pixels to better represent the marsh biomass. The NDVI-based phenological records were modeled using a nonlinear mixed model with the NLIN Procedure and the NLMIXED Procedure in SAS 9.3 developed by Mo et al. (2015). This method provides a rigorous statistical analysis for phenological curves of different vegetation that are represented by nonlinear functions. In this method, the marsh type was considered as a fixed effect with four levels—freshwater, intermediate, brackish, and saline marshes, and the four basins—the Barataria, Breton Sound, Pontchartrain, and Terrebonne basins—were considered as blocks, resulting in 16 observational units. One average NDVI value was extracted from each observational unit, i.e., one marsh type in a basin. Phenological measurements (i.e., NDVI) made on the same observational unit over time were treated as repeated-measurements. Three key phenological parameters, i.e., peak NDVI, peak NDVI day, and growing season length (bracketing days that had NDVI greater than 90% of peak NDVI), were estimated for each marsh type and each year. The influence of hurricanes on the three phenological variables was then analyzed using an analysis of variance (ANOVA) test where marsh type and hurricane were two fixed effects.

2.4. Satellite-based marsh area assessment

The Landsat CDR data were also used to study the impacts of hurricanes on the marsh area. Twenty-five cloud-free Landsat 5 TM datasets collected from 2005 to 2011, from the year of Katrina to two years after Gustav were used in the analysis (Fig. A1). The Landsat 5 TM was decommissioned in 2011, and so it was not able to provide information on marsh area change for Isaac. We did not include the Landsat 7 data in the area assessment because the Scan Line Corrector (SLC) on the Landsat 7 failed in 2003, and so the Landsat 7 data collected after 2003 are not usable for marsh area estimation (Andrefouet et al., 2003). The marsh area was estimated using the CFMask that comes with the Landsat CDR. This study only classified the land cover as land or water. The accuracy of the marshland classification was assessed using the Landsat CDR data and the USGS Digital Orthophoto Quadrangle (DOQs) data collected in Barataria basin within two days in 1998, 1999, and 2005, using a total of eight pairs of Landsat and DOQs data (Mo et al., 2019a). For each dataset, 100 validation points stratified by the land cover classes were generated randomly within the DOQ data footprint. The overall accuracy of the classification—calculated as the number of correctly classified sites/the number of the total sites—is 0.89 ± 0.04% (mean ± standard deviation). To account for the impacts of tidal conditions on the marsh area estimation, we acquired the water level information at the time of acquisition of each Landsat image from the NOAA station # 8761724 at Grand Isle, Louisiana, USA (Tides and Currents). The marsh area changes over time were examined using a regression model where time and water level were the independent variables and the marsh area was the dependent variable.

2.5. Ground-based soil characteristics and water quality assessments

Evaluating the soil characteristic changes before and after hurricanes was difficult because of the limited historical field-based data on the marsh substrates in Louisiana. We acquired soil data in 2008 from 72 sites spread throughout the study area from the Coastwide Reference Monitoring System (CRMS, Louisiana Office of Coastal Protection and Restoration, OCPR; Table A1). The soil characteristics measured were wet and dry soil pH, soil salinity, soil moisture content, organic matter, and bulk density. The measurements were taken from three soil cores of the upper 16 cm sediment from each site. The data were averaged as before-Gustav (June to July) and after-Gustav (October) data subset, and compared using a *t*-test. We also acquired long-term continuous water quality data for nutrients, i.e., nitrate and nitrite nitrogen, NNN, Kjeldahl nitrogen, KN, and phosphorus, P, from 1978 to 2018 from the Louisiana Department of Environmental Quality (Ambient Water Quality Monitoring Data; Table A2). The NNN, KN, and P concentrations have strong seasonal and interannual variations that need to be accounted for in the analysis (Mo et al., 2019b). Hence, we examine the impacts of location, year (for interannual variations), and month (for seasonal variations) on the nutrient levels using multi-factor ANOVA. We focused the analyses of the soil characteristics and water quality data within the Breton Sound basin, which was found in the early results of this study to be the most impacted area during the different hurricanes.

3. Results

3.1. Marsh biomass change before and after hurricane

The NDVI changes in the study area during the senescence period were dramatically different in the hurricane years and in the non-hurricane years from 2004 to 2015 (Fig. A2). In the non-hurricane years, the NDVI of the entire study area decreased generally less than 5% during late-August, and less than 25% during September. In the hurricanes years of 2005, 2008, and 2012, the NDVI values decreased over 50% in the Breton Sound basin during late-August, and over 50% in most of the study area during September. The gap filling process of the MOS13Q1 data—for pixels that did not have reliable data collected during the 16-day acquisition windows—may have added noise to the results, but the general difference between the hurricane and the non-hurricane years is highly evident. This suggests that the biomass damage, estimated by a NDVI decrease, was due to hurricanes, not due to normal senescence. Moreover, although the hurricane paths were quite different—the path of Katrina was over the Breton Sound and the paths of Gustav and Isaac were over the Terrebonne Bay—the spatial patterns

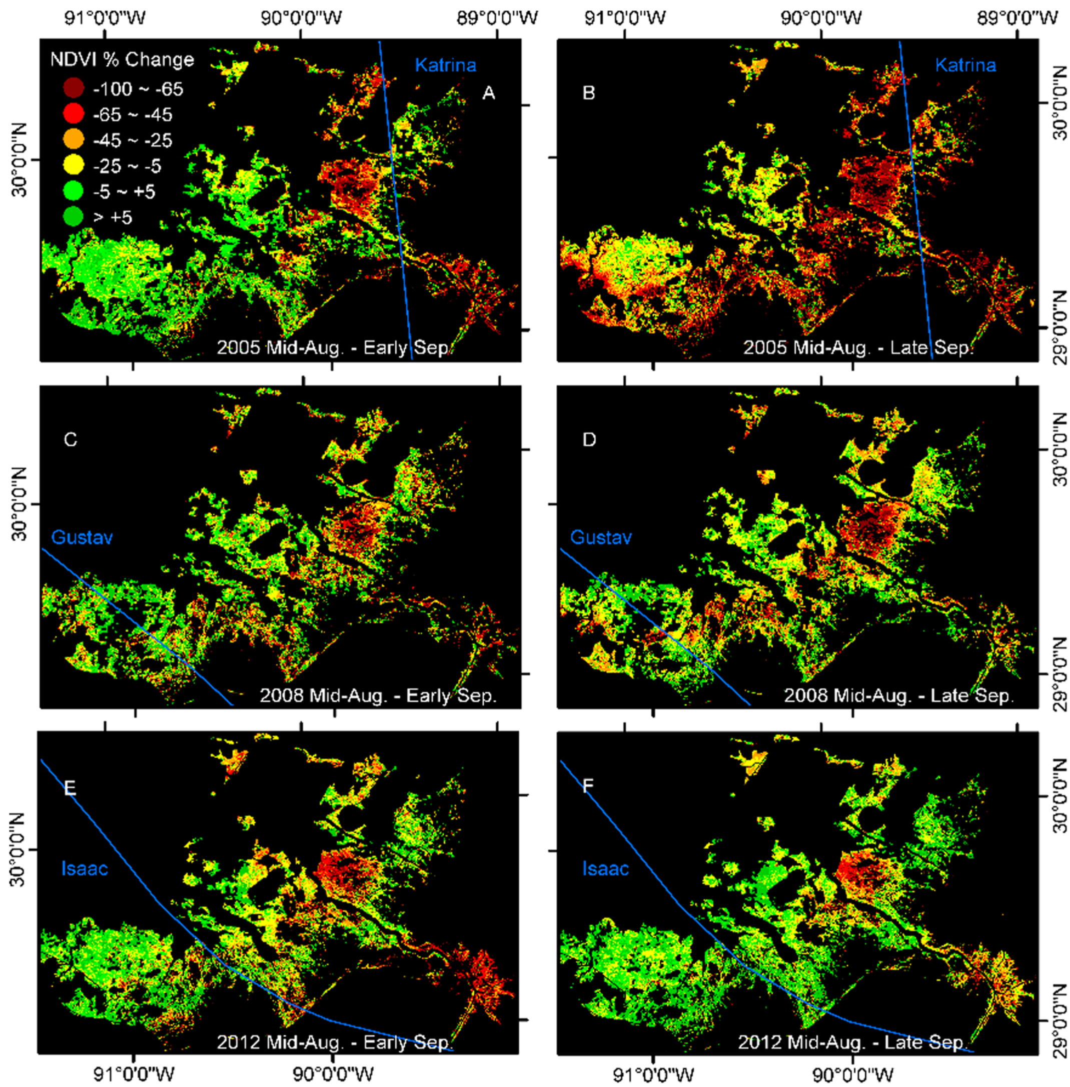

Fig. 2. MODIS-based Normalized Difference Vegetation Index (NDVI) comparison of one week before to (A) one week after Katrina, (B) one month after Katrina, (C) one week after Gustav, (D) one month after Gustav, (E) one week after Isaac, and (F) one month after Isaac. Hurricanes Katrina, Gustav, and Isaac made landfall on the coast on August 29th, 2005, September 1st, 2008, and August 29th, 2012, respectively. The NDVI changes were calculated using two MODIS 16-day composites as % NDVI change = $(NDVI_{after} - NDVI_{before})/NDVI_{before}$. The color scheme from green to red indicates % NDVI changes of −100 to −65%, *dark red*; −65 to −45, *red*; −45 to −25, *orange*; −25 to −5 *yellow*; −5 to 5%, *light green*; and > 5%, *dark green*. The paths of the hurricanes are indicated in *blue lines*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the NDVI changes in the hurricane years were similar: the largest NDVI decrease occurred in the intermediate and brackish marshes in the Breton Sound (Fig. 2).

The decrease of the NDVI of marshes in the Terrebonne and Barataria basins between mid-August and late September in 2005 was more pronounced compared to that in 2008 and 2012. This decrease possibly reflects the fact that impacts from Hurricane Katrina were magnified by Hurricane Rita, which tracked just southwest of the study area before making landfall at the Louisiana/Texas border on September 24th. This study focuses on the Breton Sound basin where the most severely impacted occurred during different hurricanes, and so the following discussion is limited to the impacts of Katrina in 2005.

3.2. Marsh phenological changes in the hurricane years

The phenological records for the study years were well-described by the models, with pseudo-R^2 ranges from 0.51 to 0.99 (Table A3). An exception was the record of saline marshes in 1994. Due to the high cloud coverage, the phenological parameters of saline marshes in 1994 could not be estimated. The peak NDVI was significantly different among marsh types ($P < 0.05$), but was not significantly different between the hurricane and normal years (Fig. 3A). Freshwater marshes had the highest peak NDVI, followed by intermediate, brackish, and saline marshes (around 0.7, 0.6, 0.5, and 0.4, respectively). Generally, freshwater marshes have a higher primary aboveground production than saline marshes (Good et al., 1978; Waide et al., 1999), and this trend is also reflected in NDVI measurements (Mo et al., 2018).

The peak NDVI day was significantly influenced by the presence of hurricanes ($P < 0.05$) and not by marsh type (Fig. 3B). The peak NDVI day of marshes in the normal years was in early July, and in the hurricane years the peak NDVI day was in mid-June. The growing season length was significantly affected by both marsh type and the presence of hurricanes ($P < 0.05$ in both cases). The growing season of saline marshes was the longest, followed by brackish, intermediate, and freshwater marshes (around six, five, four, and four months, respectively; Fig. 3C). The growing season lengths of all marsh types were

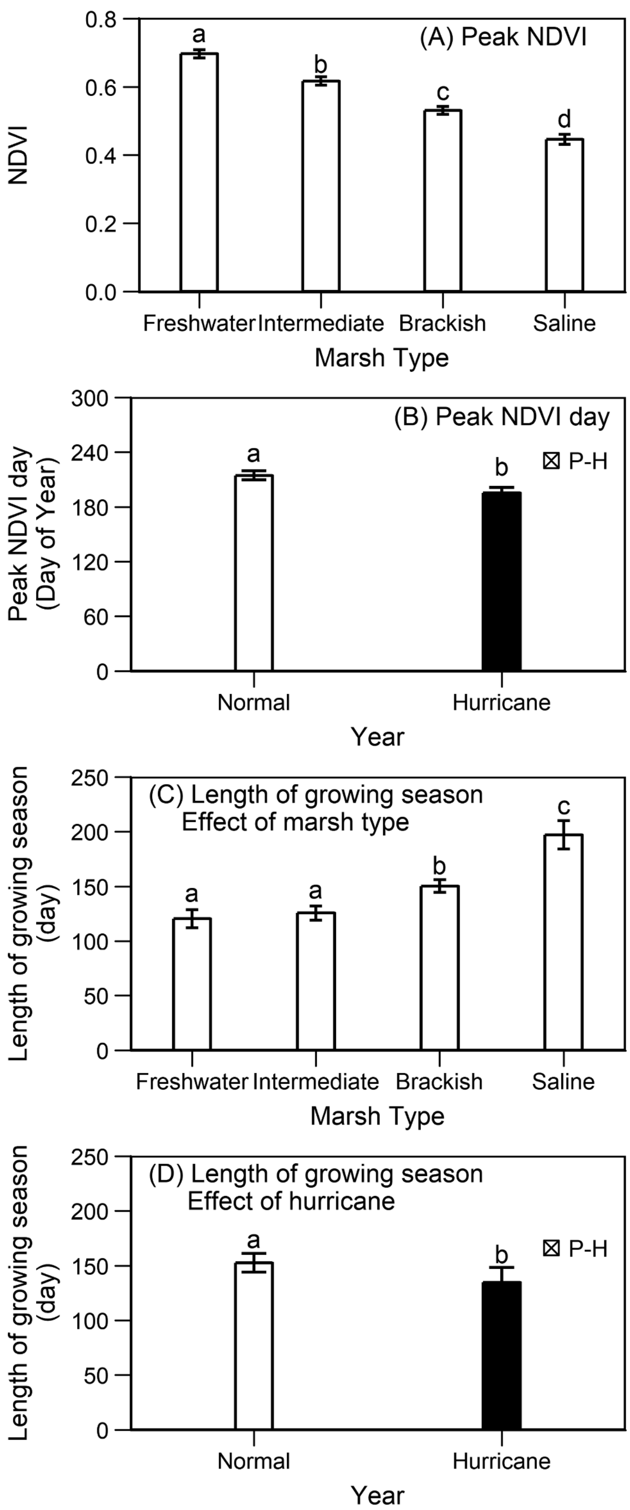

Fig. 3. Peak Normalized Difference Vegetation Index (NDVI; Panel A), peak NDVI day (Panel B), and growing season length (Panel C and D) of the marshes in the normal years, the hurricane years, and the post-hurricane year. Different lower-case letters on top of the bars indicate significant differences ($P < 0.05$). The peak NDVI was significantly different among marsh types, but not between the hurricane and normal years (Panel A). The peak NDVI day was significantly influenced by the presence of hurricane, but not by marsh type (Panel B). The growing season length was significantly affected by both marsh type and the presence of hurricane (Panel C and D). The phenological parameters of the post-hurricane year (P-H), 2009, are indicated in *squares*.

shortened by the presence of hurricanes by about one month (Fig. 3D). The earlier onset of senescence in the hurricane years was consistent with the large decrease in NDVI after each hurricane. The peak NDVI day and growing season length of the marshes in 2009 (one year after Gustav) were similar to those in the normal years (Fig. 3B and D), suggesting that the effects of hurricanes on the marsh phenology did not continue into the next year.

3.3. Marsh area change before and after hurricane

This section focuses on the intermediate and brackish marshes in the Breton Sound basin, which were the most impacted area during all three hurricanes. The marsh area decreased after Katrina in 2005 by 50.5 and 37.7% for intermediate and brackish marshes, respectively (based on the Landsat images taken on June 19th, at water level 0.291 m, and October 9th, at water level 0.075 m; Fig. 4). Afterward, the marsh area steadily increased in 2006 and 2007, and reached the pre-Katrina conditions by early 2008. After Gustav, the marsh area again dramatically decreased by 38.5 and 8.9% for intermediate and brackish marshes, respectively (based on images taken on August 30th, at water level 0.326 m, and October 1st, at water level 0.207 m). The marshes area progressively increased in 2009 and 2010. It should be noted that, while we have filtered out the water pixels, the marsh area estimation based on satellite images was still influenced by the water levels at the image acquisition time. In this case, the two before-hurricane images were collected at higher water levels than the two after-hurricane images, hence the decreased areas were probably underestimated. For a more quantitative understanding of the impacts of hurricanes on the marsh area over a longer time frame, we analyzed impact of time and water level on the marsh area using data from 2005 to 2010 (as shown in Fig. 4). It was found that the impact of the time factor was not statistically significant (Table A4).

3.4. Spatial and temporal variations of the environmental variables

This section focuses on the most severely impacted intermediate and brackish marshes in the Breton Sound basin. We found that the wet and dry soil pH, soil salinity, and bulk density did not significantly change after Gustav, while the soil moisture and organic matter did ($P < 0.1$ in both cases; Fig. 5). The increase in soil moisture probably resulted from the flooding brought by the storm surges, and the increase in organic matter probably resulted from the accumulating plant debris.

Examining the water quality data over the past 40 years—but not changes before and after hurricane as for the soil characteristics—we found that the high-damage region had significantly higher NNN and KN concentrations than the low-damage region ($P < 0.01$ in both cases), while the P concentrations in the two regions were not significantly different. Moreover, it was shown that there was an increasing trend over time for the NNN concentration. The NNN concentrations of the two regions were similar during the 1980s, but the NNN concentration in the high-damage region increased substantially in the 1990s and was 3 to 8 times higher than the low-damage region after 2000 (Fig. 6).

4. Discussion

4.1. How do hurricanes affect the biomass and area of the marshes?

The Atlantic tropical cyclone activity peaks in a roughly eight-week period from mid-August to mid-October when the air above the ocean has low wind shear, warm temperature, and high atmospheric moisture (NOAA, 2016). Hurricanes Katrina, Gustav, and Isaac all made landfall in southeast Louisiana during those conditions. Hurricanes may damage

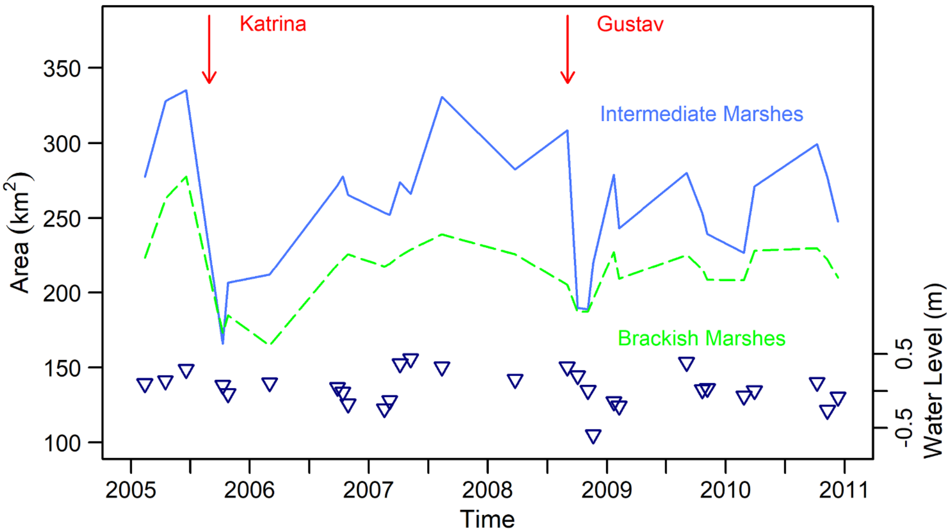

Fig. 4. Area of intermediate (*solid line*) and brackish (*dash line*) marshes in the Breton Sound basin, Louisiana, USA, from 2005 to 2010 (left axis). The water levels at the acquisition time of the Landsat images are shown by *blue triangles point down* (right axis). The dates of hurricanes Katrina and Gustav are indicated by *arrows*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

marsh plants through intense wind and wave actions, sediment burial, and saltwater intrusion, all of which can be reflected by a NDVI decrease before-and-after-hurricanes as documented in the literature and in this study (Barras, 2006; Spalding and Hester, 2007; Howes et al., 2010; Morton and Barras, 2011). This study further shows that the decrease in biomass led to a quicker senescence of marshes in the hurricane years. Yet, the impacts on the marsh biomass seem to occur only in the hurricane years. We found that the phenology of the marshes, i.e., the peak biomass and growing season length, in 2009, a post-hurricane year, was similar to the phenology in the normal years. In a field-based study, Mckee and Cherry (2009) also observed that the aboveground biomass of the marshes in the Pontchartrain basin reached

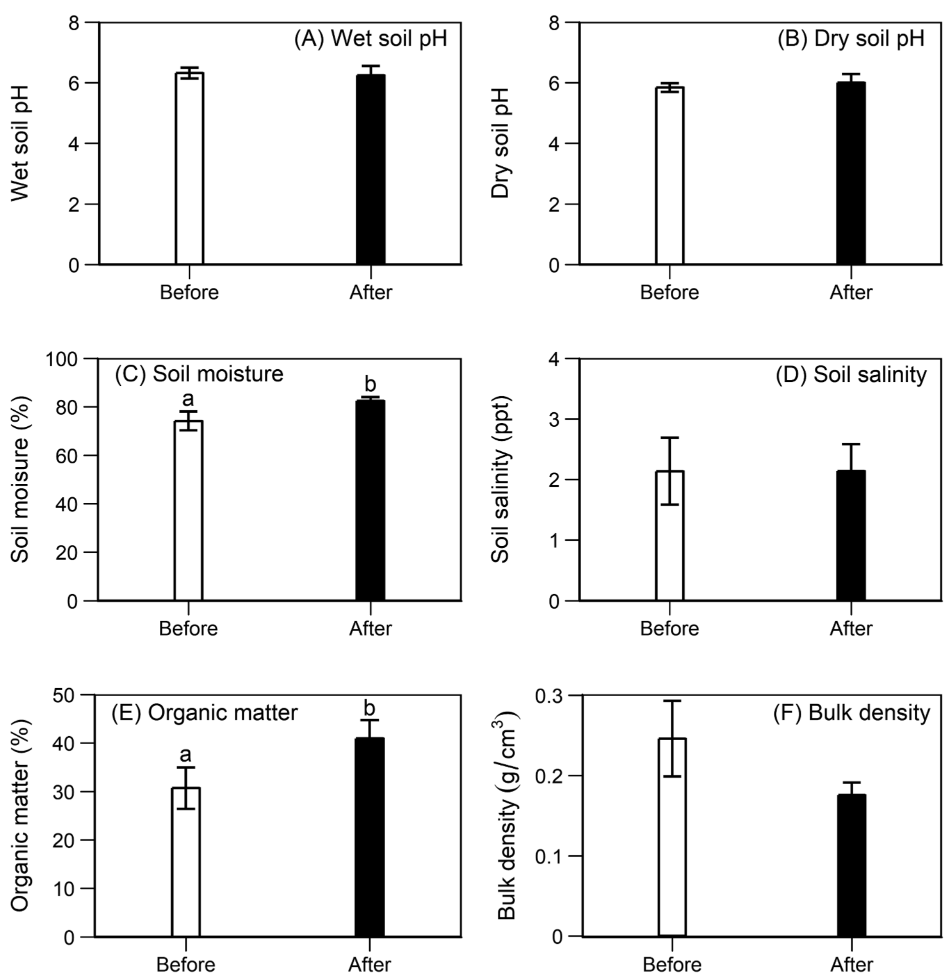

Fig. 5. Marsh soil characteristics in the Breton Sound basin before and after Gustav: (A) wet soil pH, (B) dry soil pH, (C) soil moisture content, (D) soil salinity, (E) organic matter, and (F) bulk density. Different lower-case letters on top of the bars indicate significant differences ($P < 0.1$).

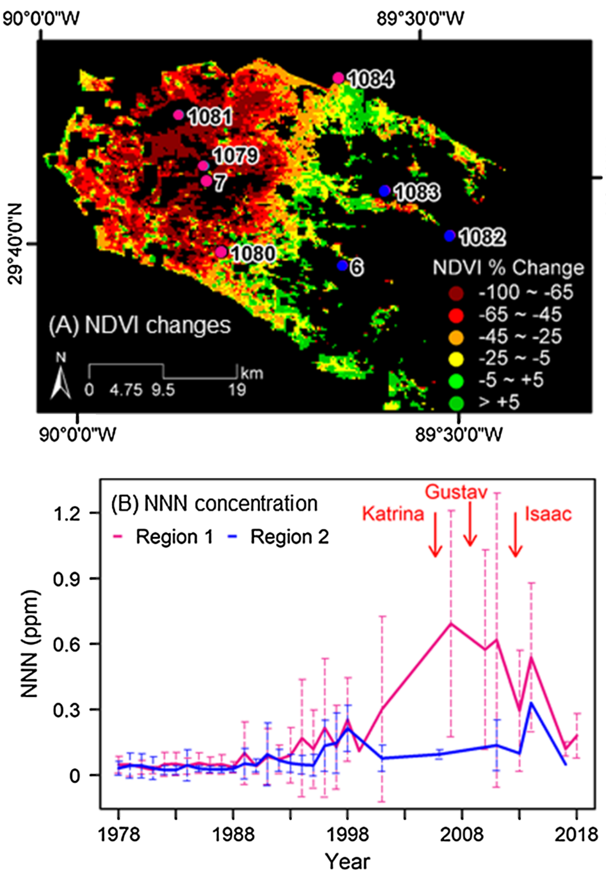

Fig. 6. Water nitrogen concentrations in coastal marshes in the Breton Sound basin, Louisiana, USA. Panel (A) shows the Normalized Difference Vegetation Index (NDVI) changes of the marshes between mid-August and late September, one month after Hurricane Gustav in 2008. The color scheme from green to red indicates the % NDVI changes of −100 to −65%, *dark red*; −65 to −45, *red*; −45 to −25, *orange*; −25 to −5 *yellow*; −5 to 5%, *light green*; and > 5%, *dark green*. Panel (A) also shows the locations of the Louisiana Department of Environmental Quality (LDEQ) stations (Table A2). The stations are assigned to Region 1 with high NDVI decrease (*deep pink dots*) and Region 2 with low NDVI decrease (*blue dots*). Panel (B) shows the annual mean and standard deviation of nitrate and nitrite nitrogen concentrations (NNN, parts per million, ppm) of Region 1 and 2 (*deep pink* and *blue*, respectively) from 1978 to 2018. The dates of hurricanes Katrina, Gustav, and Isaac are indicated by *red arrows*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the pre-Katrina level in early 2006.

The large decreases in marsh area across the coast immediately following hurricanes could result from erosion, flooding, and water ponding (Barras, 2006). Yet, this study found that the area of the intermediate and brackish marshes in the Breton Sound basin, the most impacted site during all three huricanes,progressively rebounded within two years after both hurricanes Katrina and Gustav. It should be noted that the marsh area regain could be overestimated due to dense floating vegetation with high NDVI that was classified as marshland, and the level of recovery was likely to vary among different locations within the Breton Sound (Kearney et al., 2011; Turner et al., 2019). This study finds that areas of the intermediate and brackish marshes in the Breton Sound did not change significantly with time and water level from 2005 to 2010. This result does not contradict a finding that the marsh area decreased in Louisiana over decades, because the rates of the area changes vary dramatically by locations (i.e., basins and vegetation types) and over time (i.e., 1931 untill now) (Couvillion et al., 2017; Mo et al., 2019a).

4.2. *What are the main factors impacting the resilience of the marshes?*

The levels of impact of hurricanes varied dramatically spatially, but the intermediate and brackish marshes in the Breton Sound were most affected during all hurricanes Katrina, Gustav, and Isaac. The severe damage of the marshes in the Breton Sound basin during Katrina was attributed to the proximity to the hurricane's track (Day et al., 2013). However, although the paths of Gustav and Isaac were over the Terrebonne basin, the marshes in the Breton Sound basin showed more damage than marshes in the Terrebonne basin. Our results, therefore, indicated that the distance to the hurricanes' track may not be a key factor in controlling the impact of hurricanes.

The factors controlling the hurricane' impacts are not entirely clear, but several hypotheses can be proposed. One possible explanation is that the Breton Sound always experienced the strongest storm surges during the three hurricanes. As the cyclones in the northern hemisphere rotate counter-clockwise, hurricanes Katrina, Gustav, and Isaac generated westward/northwestward winds when making landfall in Louisiana (Forbes et al., 2010; Dietrich et al., 2011a; Dietrich et al., 2011b; Berg, 2013). Katrina's path was over the entrance to the Breton Sound, and thus the Breton Sound experienced the highest wind speed and storm surges (Dietrich et al., 2011b). As the track of Gustav was over the Terrebonne basin, the highest wind speeds were found in the Barataria Bay during hurricane Gustav. However, the strongest storm surges and highest inundation were in the Breton Sound (Berg, 2013), probably due to the lack of protection from the barrier islands (Forbes et al., 2010; Dietrich et al., 2011a).

However, the strong storm surges in the Breton Sound do not explain why the intermediate and brackish marshes were more damaged compared to the saline marshes that are closer to the shoreline. The intermediate and brackish marshes are acclimated to lower salinity environment than saline marshes, and thus may be more susceptible to saltwater intrusion (Spalding and Hester, 2007). This study, however, found no significant changes in soil salinity in the marsh soil before and after Gustav. It is possible that the intermediate and brackish marshes were damaged by the anoxia created by the hurricane-induced flooding—low salinity marshes are also less adapted to continuous ponding compared to the saline marshes (Mendelssohn et al., 1981; Morton and Barras, 2011)—but the soil data acquired from the CRMS was not informative one way or the other. Future soil surveys with a proper sampling scheme designed for before-and-after hurricane comparisons measuring the potentially relevant variables may provide more insights into the soil characteristic changes.

We argue that one of the reasons for the severe damage of the intermediate and brackish marshes was the high nitrogen inputs. We examined the water quality data in Breton Sound over the past 40 years and found that the nitrogen concentration as NNN in the intermediate and brackish marshes dramatically increased in the 1990s, and was several times higher than the nitrogen concentration in the saline marshes after 2000. The increase of nitrogen in the northern Breton Sound was an expected result of the Caernarvon diversion, which opened in 1991 and is designed to bring nutrients to the Breton Sound estuary (Louisiana Department of Natural Resources, 2003). Previous studies reported that, inside the Breton Sound, the decrease of marsh area was higher and the recovery was lower after Katrina in the Caernarveon-influenced area compared to the area outside of the diversion's flow path (Kearney et al., 2011; Turner et al., 2019). Howes et al. (2010) attributed the high damage in the low salinity marshes to the weaker soil profile compared to the saline marshes. Several field-based studies showed that nutrient enrichment decreased coastal marshes'

belowground biomass and increased their root mat decomposition, and thus led to a weaker soil profile (Bulseco et al., 2019; Deegan et al., 2012; Ket et al., 2011; Swarzenski et al., 2008, and Turner et al., 2009).

4.3. *The synergistic effects of climatic and anthropogenic stresses*

Twenty-seven percent of the Louisiana coastal marshes existing in 1932 were lost by 2010, and, notably, 40% of the marshes in the Breton Sound basin were lost (estimated using linear models based on data from Couvillion et al.). The extensive wetland loss is a result of many confounding factors in the region. The relative sea-level rise rate in the Louisiana coast is among the world's highest, at 12 ± 8 mm yr^{-1}; particularly in the northern Breton Sound the rate is around 20 mm yr^{-1} (Jankowski et al., 2017). River engineering such as dam and levee constructions reduced sediment delivery by over 50% during the last 150 years, leading to a sediment deficit in the Mississippi River delta, including the Breton Sound estuary (Blum et al., 2009, Morang et al., 2013). Subsurface fluid withdrawal activities, i.e., oil and gas extraction, that peaked during the early-mid 20th century may have greatly exacerbated subsidence and marsh submergence (Morton et al., 2005). The over 16,000 km of canals and navigation channels—primarily for the oil and gas industry—dredged across the Louisiana coast since 1900, and specifically over 30 km in the Breton Sound, caused significant marsh loss through hydrological changes (Hoekstra, 2003; Turner and McClenachan, 2018).

The Caernarvon diversion implemented in 1991 was designed to re-introduce freshwater, sediments, and nutrients into the marshes and bays of the Breton Sound estuary (Louisiana Department of Natural Resources, 2003). This study examined the water quality from 1978 to 2018 and found that the nitrogen levels in the Breton Sound estuary substantially increased in the 1990s, especially in the upper estuary. The nutrient enrichment is likely to lead to a weaker soil profile by decreasing the marshes' root growth and increasing their root mat decomposition (Deegan et al., 2012; Ket et al., 2011; Swarzenski et al., 2008; Turner et al., 2009). A weak soil profile can make the marshes more susceptible to erosion during infrequent high-energy events, such as hurricanes, and regular low-energy events, such as tides (Swarzenski et al., 2008). Moreover, the promoted decomposition of the marsh substrates due to increased nutrient availability may also impair the marshes' resilience against sea-level rise (Bulseco et al., 2019; Craft, 2007).

Through a long-term research involving multiple hurricanes, we found that the marshes can be quite resilient to hurricanes at a landscape scale: significant loss of marsh biomass and area was observed immediately after hurricanes, but general recovery was found in the next one to two years. However, we also found that areas with greater nutrient concentrations were more impacted by strong hurricanes, emphasizing the need for more research on the outcomes of nutrient inputs to the marshes, especially in combined with other stressors. Our results not only highlight the resilience of coastal marsh ecosystems against hurricanes, but also underscore the profound synergistic effects of climatic and anthropogenic factors on the sustainability of coastal ecosystems and the necessity of better understanding the long-term outcomes of large ecosystem management projects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Figs. A1 and A2 and Tables A1–A4.

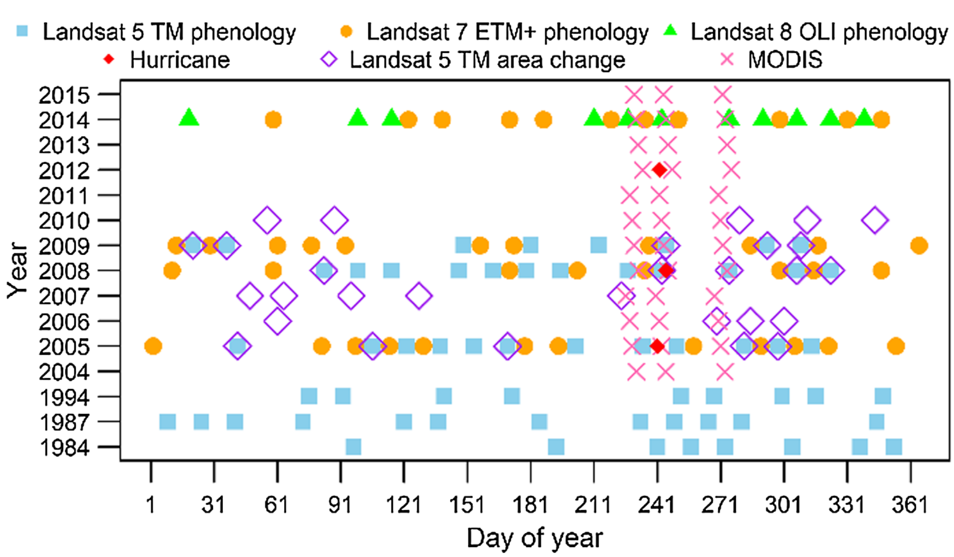

Fig. A1. Sampling dates of satellite imagery used in this study. The phenological modeling uses imagery from Landsat 5 Thematic Mapper (TM; *blue squares*), Landsat 7 Thematic Mapper Plus (ETM+; *orange circles*), and Landsat 8 Operational Land Imager (OLI; *green triangles*). The marsh area changes were examined using Landsat 5 TM imagery (*open purple diamonds*). The Normalized Difference Vegetation Index (NDVI) changes were examined using MODIS NDVI 16-day composite (*pink crosses*). The dates of hurricanes Katrina, Gustav, and Isaac are indicated by *red filled diamonds*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

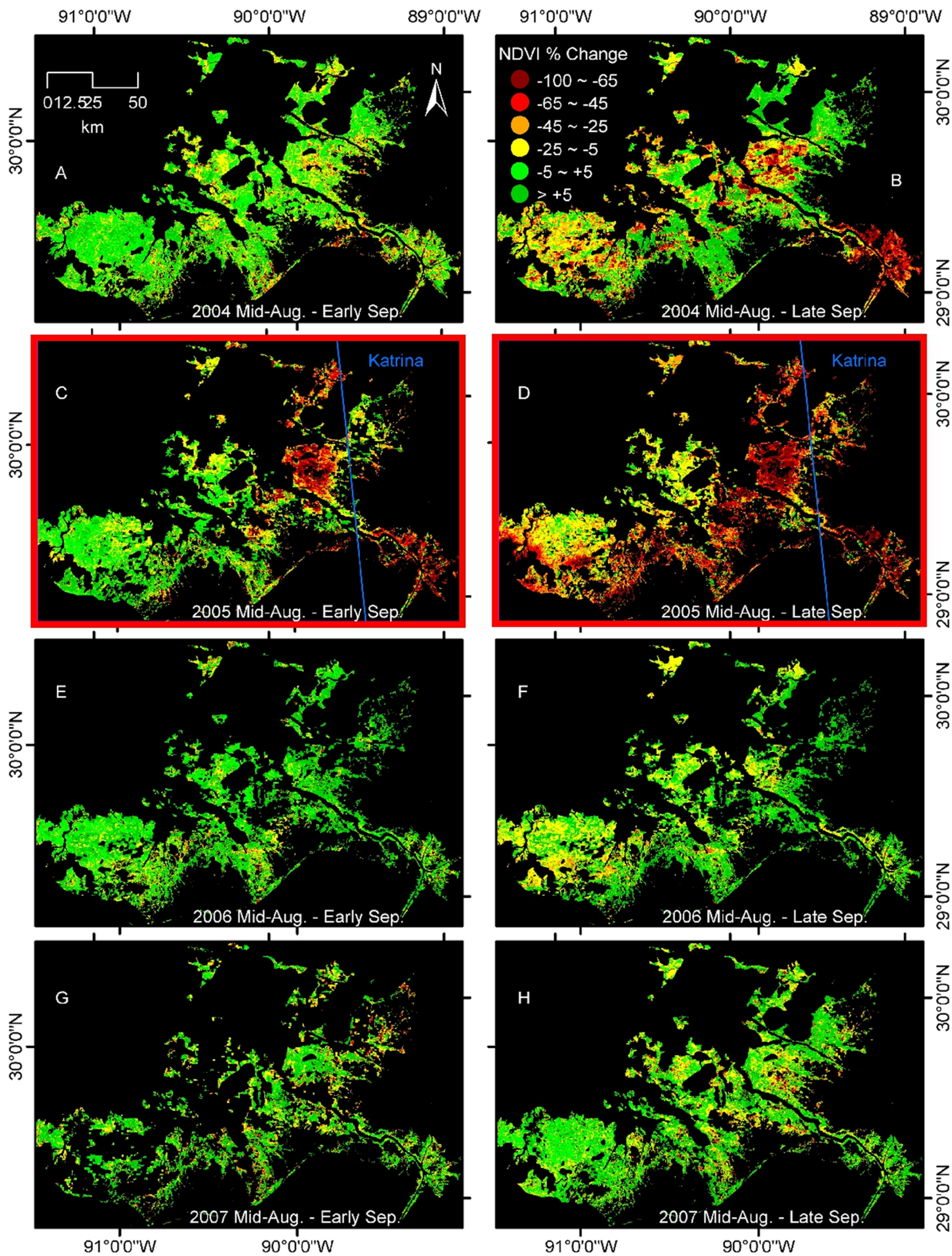

Fig. A2. MODIS-based Normalized Difference Vegetation Index (NDVI) change between mid-August and early September (Panels A, C, E, G, I, K, M, O, Q, S, U, and W) and between mid-August and late September (Panels B, D, F, H, J, L, N, P, R, T, V, and X) from 2004 to 2015. Hurricanes Katrina, Gustav, and Isaac made landfall on the coast on August 29th, 2005, September 1st, 2008, and August 29th, 2012, respectively. The NDVI changes were calculated using two MODIS 16-day composites as % NDVI change = $(NDVI_{after} - NDVI_{before})/NDVI_{before}$. The color scheme from green to red indicates % NDVI changes of −100 to −65%, dark red; −65 to −45, red; −45 to −25, orange; −25 to −5 yellow; −5 to 5%, light green; and > 5%, dark green. The paths of the hurricanes are indicated in *blue lines*. The hurricanes years are highlighted with *red frames*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

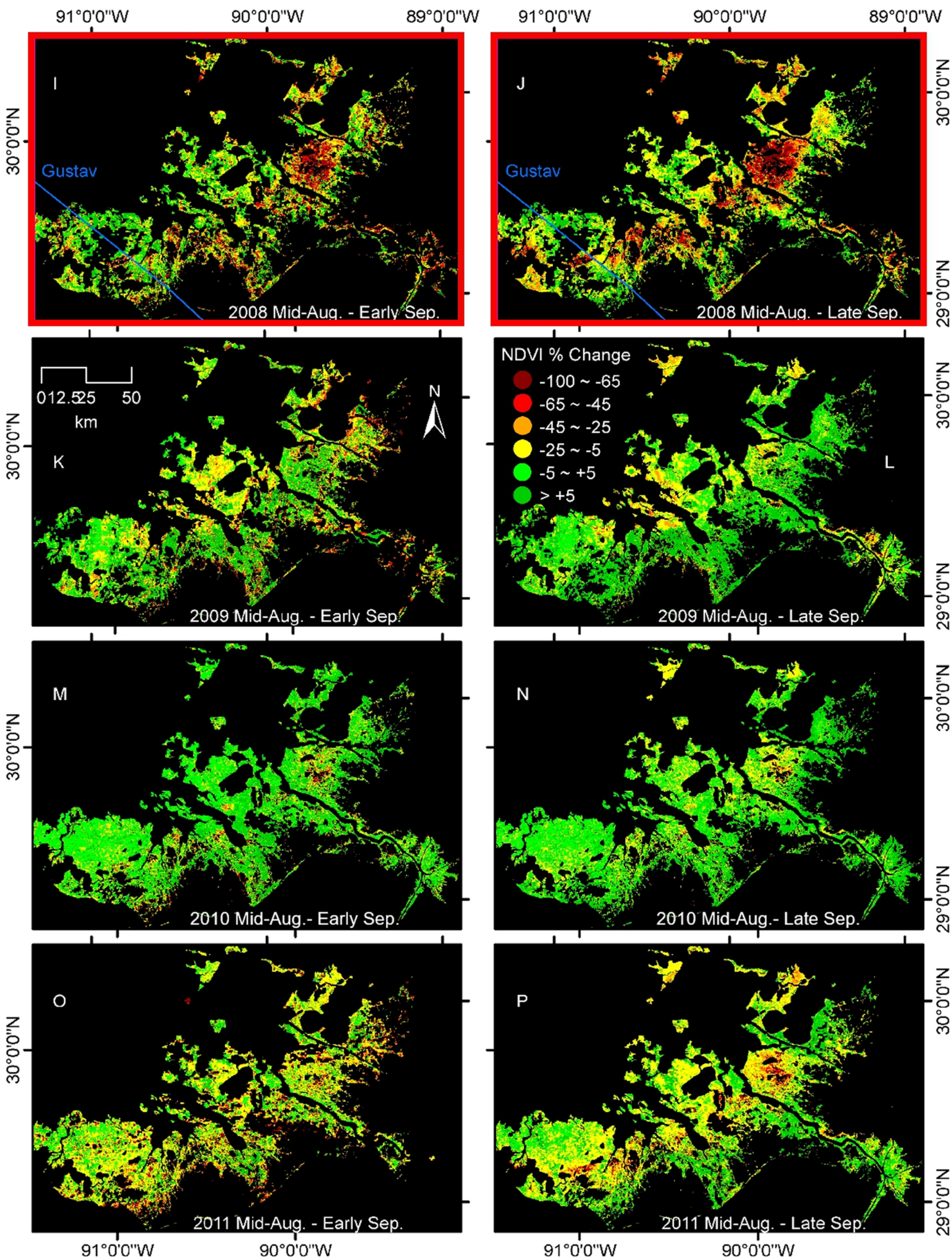

Fig. A2. (*continued*)

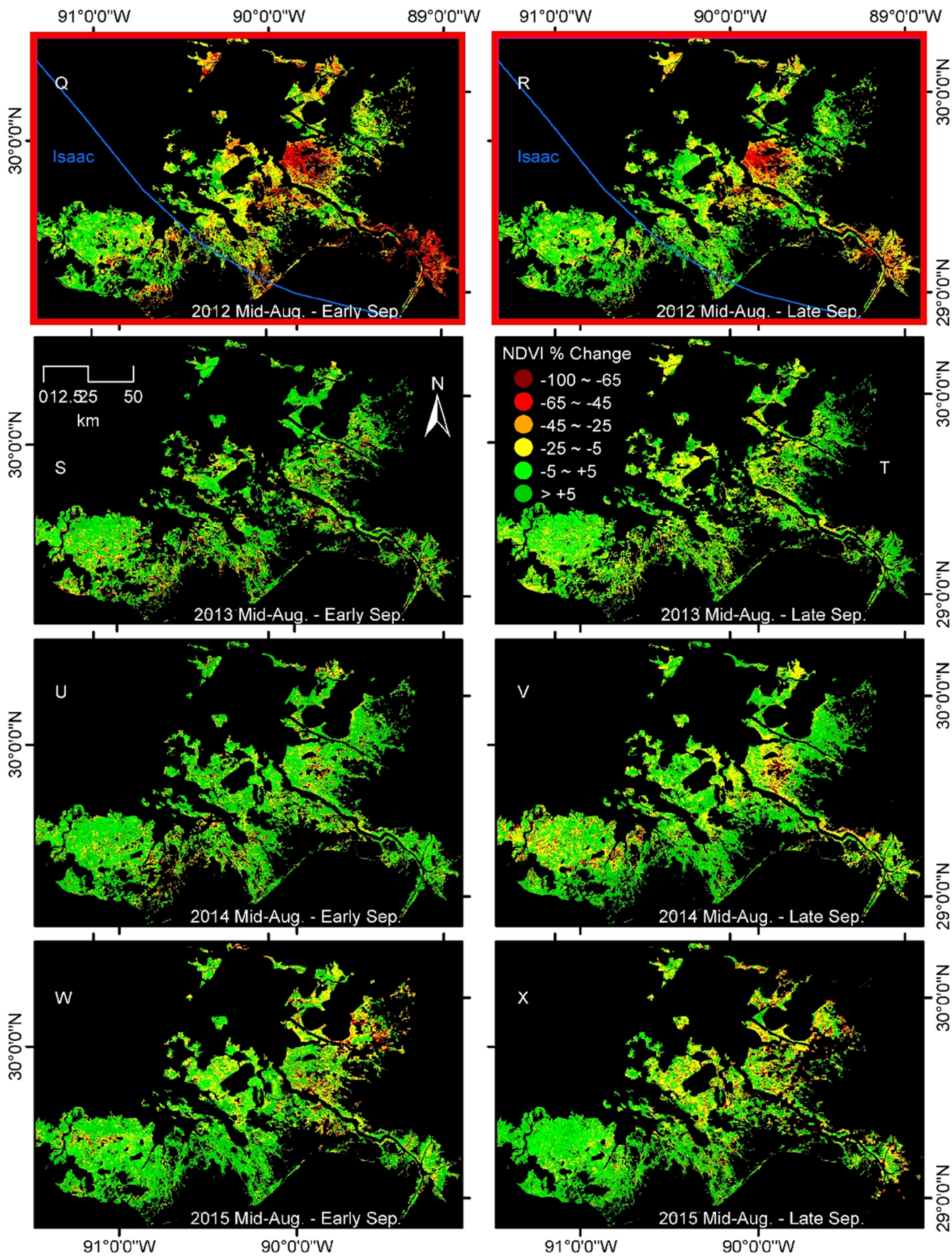

Fig. A2. (*continued*)

Table A1
Sampling sites of the ground-based soil characteristic data. Stations inside the Barataria basin used in the before and after hurricane analysis are indicated in **bold**.

Site	Station ID	Sample date	Latitude	Longitude	Site	Station ID	Sample date	Latitude	Longitude
1	CRMS0409	15-Jan-2008	-90.92001377	29.47872464	**37**	CRMS0287	17-Jun-2008	-90.0148497	29.68598632
2	CRMS0411	15-Jan-2008	-90.9510532	29.4980811	**38**	CRMS3626	17-Jun-2008	-89.85425676	30.10760402
3	CRMS0301	17-Jan-2008	-91.227144	29.50575764	**39**	CRMS4103	17-Jun-2008	-90.03987232	29.65864383
4	CRMS2881	17-Jan-2008	-91.01222827	29.47242951	**40**	CRMS4406	17-Jun-2008	-89.7279624	30.20185516
5	CRMS2991	20-Feb-2008	-90.4458245	29.6370288	**41**	CRMS4407	17-Jun-2008	-89.73044818	30.22272851
6	CRMS0241	10-Mar-2008	-90.50807488	29.7129591	**42**	**CRMS3800**	18-Jun-2008	-89.66777312	29.84004898
7	CRMS2887	9-Apr-2008	-90.91518824	29.52200074	**43**	CRMS4548	18-Jun-2008	-89.66920519	29.86138347
8	CRMS2825	2-May-2008	-90.44418019	29.49829692	**44**	**CRMS4551**	18-Jun-2008	-89.60404882	29.85326565
9	CRMS0414	7-May-2008	-90.94344604	29.70033071	**45**	CRMS4557	18-Jun-2008	-89.5735689	29.82441754
10	CRMS5770	7-May-2008	-90.90499791	29.75830707	**46**	CRMS0006	20-Jun-2008	-89.98231662	30.26354045
11	CRMS5536	9-May-2008	-91.13001812	29.97044871	**47**	CRMS0260	20-Jun-2008	-89.85399647	29.53421943
12	CRMS4045	23-May-2008	-91.0098761	29.38053569	**48**	CRMS0263	20-Jun-2008	-89.8868781	29.5532115
13	CRMS0063	2-Jun-2008	-90.64092642	30.12831429	**49**	CRMS0276	20-Jun-2008	-89.94534387	29.61953963
14	CRMS0399	2-Jun-2008	-91.10536239	29.29989076	**50**	CRMS2854	20-Jun-2008	-89.98329503	30.30080749
15	**CRMS3639**	2-Jun-2008	-89.85014641	29.90783463	**51**	CRMS0058	24-Jun-2008	-90.53733978	30.16557736
16	**CRMS3641**	2-Jun-2008	-89.85537192	29.91907845	**52**	CRMS0385	24-Jun-2008	-90.60315159	29.41045064
17	**CRMS3664**	2-Jun-2008	-89.82932956	29.91212377	**53**	CRMS2830	24-Jun-2008	-90.34482394	30.03994756
18	CRMS5255	2-Jun-2008	-90.60141787	30.19270777	**54**	CRMS6299	24-Jun-2008	-90.350497	30.0484233
19	CRMS5373	2-Jun-2008	-90.63106548	30.10060581	**55**	CRMS2627	25-Jun-2008	-89.18434292	29.23178853
20	CRMS5414	2-Jun-2008	-90.63366308	30.15827616	**56**	CRMS2634	25-Jun-2008	-89.25981081	29.23051532
21	CRMS0272	3-Jun-2008	-89.69373049	29.42056401	**57**	CRMS4448	25-Jun-2008	-89.23419768	29.2139556
22	CRMS0282	3-Jun-2008	-89.76037175	29.49866534	**58**	CRMS0398	27-Jun-2008	-90.9173538	29.38631291
23	CRMS45291	3-Jun-2008	-89.82174907	29.47059533	**59**	**CRMS0131**	17-Jul-2008	-89.88847575	29.68851412
24	CRMS0047	4-Jun-2008	-90.53396374	30.13439411	**60**	CRMS0008	10-Oct-2008	-90.68522542	30.22828565
25	CRMS0089	4-Jun-2008	-90.5807722	30.13162119	**61**	CRMS0038	10-Oct-2008	-90.67761811	30.21340228
26	CRMS0090	4-Jun-2008	-90.56145808	30.16079628	**62**	CRMS0061	10-Oct-2008	-90.63915295	30.22055366
27	CRMS3054	4-Jun-2008	-90.35758375	29.72108034	**63**	**CRMS0117**	28-Oct-2008	-89.91795634	29.80891258
28	CRMS4218	4-Jun-2008	-90.16470053	29.56343256	**64**	**CRMS0120**	28-Oct-2008	-89.85632637	29.84453232
29	CRMS3166	5-Jun-2008	-90.28882017	29.85881873	**65**	**CRMS4355**	28-Oct-2008	-89.82401937	29.84034984
30	CRMS3169	5-Jun-2008	-90.27205976	29.8891128	**66**	**CRMS0114**	29-Oct-2008	-89.91693783	29.75885557
31	CRMS3985	6-Jun-2008	-90.1491592	29.71739379	**67**	**CRMS0121**	29-Oct-2008	-89.81990307	29.69354854
32	CRMS4245	6-Jun-2008	-90.13506839	29.67218259	**68**	**CRMS0128**	29-Oct-2008	-89.94789373	29.83169392
33	CRMS0403	11-Jun-2008	-91.13748363	29.76741585	**69**	**CRMS0146**	29-Oct-2008	-89.72617226	29.72921746
34	CRMS3680	12-Jun-2008	-89.79204523	29.51251889	**70**	BA02-150	30-Oct-2008	-90.26255883	29.54659031
35	CRMS0097	16-Jun-2008	-90.65938678	30.15472354	**71**	BA02-83	4-Nov-2008	-90.26385128	29.49116313
36	CRMS5845	16-Jun-2008	-90.68361535	30.18351471	**72**	CRMS4107	19-Dec-2008	-89.85332608	30.05482826

Table A2
Sampling sites of the ground-based water quality data.

Site Number	Subsegment	Site	Latitude	Longitude
6	LA042208_00	Bay Gardene (Bayou Lost) East of Pointe a la Hache	-89.63221	29.6004
7	LA042104_00	Petit Lake south of Delacroix	-89.80011	29.71684
1079	LA042103_00	Bayou Gentilly near Lake Petit	-89.80096	29.73427
1080	LA042102_00	Oak River at the Koch Gateway pipeline crossing	-89.78943	29.63294
1081	LA042105_00	Lake Lery	-89.82737	29.79681
1082	LA042202_00	Breton Sound near Mozambique Point	-89.48684	29.62018
1083	LA042207_00	Lake Calebasse	-89.566	29.681
1084	LA042101_00	Bayou Loutre at Breton Sound Marina	-89.61228	29.81817

Table A3
Pseudo R^2 of the phenological modeling of the freshwater, intermediate, brackish, and saline marshes in the normal years (1984, 1987, 1994, and 2014), in the hurricanes years (2005 and 2008), and in the post-hurricane year (2009).

Marsh Type	Normal Years				Hurricane Years		Post-hurricane Year
	1984	1987	1994	2014	2005	2008	2009
Freshwater	0.97	0.97	0.87	0.91	0.94	0.92	0.94
Intermediate	0.99	0.95	0.88	0.89	0.92	0.81	0.91
Brackish	0.91	0.93	0.82	0.84	0.91	0.74	0.85
Saline	0.57	0.85	–	0.66	0.83	0.51	0.78

Table A4
Impacts of time (yr) and water level (m) on the marsh area (km^2) of the intermediate and brackish marshes in the Breton Sound basin, the most impacted area during all Hurricanes Katrina, Gustav, and Isaac from 2005 to 2010.

Coefficients	Estimate	Standard Error	t value	P
Intermediate marsh area				
Intercept	−487.8	8840.2	−0.0555	0.956
Time	0.3707	4.4	0.084	0.934
Water level	65.6	34.6	1.894	0.069
Brackish marsh area				
Intercept	1258.9	5098.6	0.247	0.807
Time	−0.5198	2.5390	−0.205	0.839
Water level	25.8	20.0	1.293	0.207

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