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Productivity and Resilience: Long-Term Trends and Storm-Driven Fluctuations in the Plant Community of the Accreting Wax Lake Delta

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Abstract River deltas are dynamic geologic features where the plant community engages in critical feedbacks with geomorphology, and plant community development is impacted by both riverine and coastal drivers. A vegetation index (NDVI) calculated from a time series of 54 peak growing season Landsat-5 TM and Landsat-7 ETM+ images was used to assess the long-term trends and storm event-driven changes in the vegetation community associated with the Wax Lake Delta, an actively accreting subdelta of the Mississippi River. Multiple regression models were developed to explain variation in the vegetated area of the delta and mean delta NDVI from 1984 to 2011 as a function of date, hydrology, and seasonality. The models indicate that both vegetated area and mean NDVI increased over time from 1984 to 2011. Productivity measures following Hurricanes Lili (2002), Rita (2005), and Ike (2008) represented statistical outliers; significant decreases in NDVI following these storms suggest that hurricanes passing directly over or to the west of the delta result in short-term disturbance to the plant community, most likely related to saltwater intrusion associated with storm surge. However, in each case, both vegetated area and mean NDVI recovered to the long-term trend by the following growing season. These results demonstrate that the freshwater marshes within this mineral-rich, accreting delta are increasing in productivity as the delta matures and are extremely resilient to coastal storm disturbance.

Keywords River deltas · Wetland vegetation · Normalized difference vegetation index (NDVI) · Hurricane disturbance · Coastal wetlands · Primary production

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Introduction

River deltas are ephemeral features at geologic timescales. They occur wherever rivers deliver sediment to a coastline faster than it is removed by coastal erosion and are strongly influenced by both riverine and coastal processes (Day and Giosan 2008; Wright 1985). They are also dynamic systems, constantly changing with fluctuations in sediment delivery by the river, storage within the channel and its floodplains, and reworking by waves, tides, and coastal storm events (Yang et al. 2003; Yang et al. 2010; Tweel and Turner 2012b; Conner et al. 1989; McManus 2002; Wright and Coleman 1973). The plant communities that develop on river deltas both respond to and influence this continual process of geomorphic change (Corenblit et al. 2011; Corenblit et al. 2007). On the one hand, plant distributions within river deltas are strongly controlled by physical factors such as the frequency, duration, and depth of flooding, strength of channel flow, substrate, and frequency, extent, and duration of saltwater intrusion (Kandus and Malvárez 2004; Johnson et al. 1985; Cahoon et al. 2011). These factors are determined to a large part by delta geomorphology. On the other hand, the plants that colonize river deltas themselves contribute to the geomorphological development of newly emergent islands. Plants influence vertical accretion and soil formation on the developing islands by trapping sediments with their roots,

increasing sediment cohesion, reducing erosion, and contributing organic matter that changes the composition and structure of the developing soil and increases vertical accretion (White 1993; Cahoon et al. 2011; Nyman et al. 1990; Rosen and Xu 2013; Edmonds and Slingerland 2009; Marani et al. 2013; Beeson and Doyle 1995; Lorenzo-Trueba et al. 2012).

The plant communities that develop in temperate river deltas are unique within coastal environments, because the delivery of a large volume of freshwater provides the opportunity for establishment of extensive freshwater wetlands in what would otherwise be a hostile saline environment. Primary succession initiates as soon as mudflats obtain sufficient elevation to support emergent plant species (Kandus and Malvárez 2004; Fuller et al. 1984; White 1993; Cahoon et al. 2011). A rapid increase in belowground biomass occurs following colonization, as the plants forage for nutrients in the sediment (Cahoon et al. 2011). This increases the cohesion of the sediment, while the increased surface roughness provided by the aboveground stems slows flood flows and promotes further sediment trapping (Nepf and Vivoni 2000; Temmerman et al. 2005). The first colonizing plants are frequently ruderal annuals with local seed sources (White 1993; Shaffer et al. 1992). However, once perennials reach the newly emergent mudflats, they quickly become dominant, relegating the annuals to brief seasonal windows early and late in the growing season (White 1993). As establishment of the early colonizing species further increases sediment trapping compared to the bare mudflats, they create the conditions for their own replacement by superior competitors adapted to higher elevations (Shaffer et al. 1992; Kandus and Malvárez 2004). Large monotypic stands are common in deltas, particularly at the lowest and highest ends of the elevation gradient (Cahoon et al. 2011). Species richness is commonly much higher at intermediate elevations, where stress is intermediate between the high physical stress caused by frequent flooding in the low marsh and the high ecological stress caused by increased competition at higher elevations (Kandus and Malvárez 2004; Johnson et al. 1985). Overall species richness also tends to increase as river deltas mature, elevations increase, and a wider range of species is able to invade (Shaffer et al. 1992).

While the long-term trend in accreting river deltas is naturally one of biomass accumulation, disturbance events that damage the plant community or result in physical erosion and elevation loss have the potential to reset the trajectory of marsh succession. Within coastal river deltas, hurricanes and tropical storms are among the most common disturbances to marsh communities. Impacts from coastal storms can include direct physical disturbance of vegetation by strong winds, as well as extended flooding, erosion, and saltwater intrusion associated with storm surges (Rodgers et al. 2009; Bianchette et al. 2009; Morton and Barras 2011; Ramsey et al. 2001). The degree to which any particular coastal marsh experiences one or all of these forms of stress related to a given storm event depends on the size and strength of the storm, the path it takes relative to the location of the marsh, and how quickly the storm passes (Day et al. 2007; Ramsey et al. 2001; Steyer 2008). In the most extreme cases, hurricanes making direct landfall in coastal wetlands can result in direct disturbance such as uprooting of vegetation, folding of the marsh surface, or conversion of marsh to open water (Morton and Barras 2011). Indirect disturbance may also result in changes to the marsh community. Saltwater that is trapped in a marsh following a storm event can kill freshwater marsh species and promote the establishment of a more salt-tolerant community (Morton and Barras 2011; Flynn et al. 1995; Baldwin and Mendelssohn 1998). Or marshes that are repeatedly exposed to surges of saltwater from storm events may see a gradual reduction in the most salt-sensitive species and their replacement with more salt-tolerant species over time (Holm and Sasser 2001).

Hollings (1973) first defined ecological resilience as the ability of an ecosystem to absorb disturbance while still maintaining the relationships between populations and state variables that define the system's equilibrium state. A related concept is that of ecological stability, which Hollings used to describe the ability of a system to return to equilibrium following a temporary disturbance. A number of authors have since modified these definitions. Two types of resilience are now generally recognized: engineering resilience and ecological resilience. The term engineering resilience refers to the amount of time it takes for a system to return to a single equilibrium state following a disturbance (Peterson et al. 1998). Ecological resilience is a more appropriate term when more than one stable equilibria exist (Sutherland 1974; May 1977). Within this context, ecological resilience refers to the amount of disturbance that is necessary to force a system to shift from its current stable state to an alternate stable state (Peterson et al. 1998). The resilience of ecosystems is not constant, but is subject to change as a result of human-induced alterations and stresses (Gunderson 2000; Scheffer et al. 2001; Folke et al. 2004).

While tropical storms and hurricanes represent stochastic disturbances to which the plant communities in coastal river deltas have adapted over time and which create diversity at both local and landscape scales, human alteration of deltas has the potential to reduce the resilience of deltaic wetlands to such disturbances (Conner et al. 1989). Many of the world's major river deltas have been heavily altered to allow them to support human activities such as urban development and agriculture. Often, deltas have been hydrologically altered in ways that cut the wetlands in the delta off from the river floods that built and sustain them (Syvitski 2008; Syvitski et al. 2009). Removing the primary source of sediment input to the delta often leads to subsidence through the compaction and dewatering of existing sediments (Törnqvist et al. 2008; Meckel et al. 2006; Day and Giosan 2008; Morton and

Bernier 2010). It can result in dramatic land loss as deltaic wetlands are no longer able to accrete vertically at a sufficient rate to keep pace with relative sea level rise (Syvitski 2008). This problem has been further exasperated by the construction of dams in upstream watersheds, which reduce downstream sediment supply (Blum and Roberts 2009). When the natural processes that built and maintained deltas are disrupted, the resilience of deltaic wetlands is reduced and they become more vulnerable to localized stressors such as saltwater intrusion (Turner 1997), pollution (Silliman et al. 2012), fluid extraction, and storm disturbance (Steyer et al. 2013).

While much of our understanding of plant community productivity and the response of ecosystems to disturbance events comes from field research, remote sensing provides an opportunity to study these issues at the landscape level. Many of the vegetation community parameters that are commonly measured in the field and used to estimate primary production are correlated with plant spectral reflectance values in the visible and near-infrared portion of the light spectrum (Ihse and Graneli 1985; Jensen et al. 2002; Bartlett and Klemas 1981). The most commonly used remotely sensed indicator of plant productivity is the normalized difference vegetation index (NDVI) (Rouse et al. 1974). NDVI is a weighted ratio of spectral reflectance in the red and near-infrared regions of the light spectrum and has been shown to correlate strongly with live aboveground biomass, leaf area index (LAI), percent vegetation cover, and chlorophyll content (Gross et al. 1993; Jensen et al. 2002; Hardisky et al. 1983). These relationships have been demonstrated in a variety of settings, including forests, floodplains, grasslands, and both fresh and salt marshes (Gross et al. 1993; Nagler et al. 2009; White and Lewis 2011; Hardisky et al. 1983; Drake 1976; Dong et al. 2003; Paruelo et al. 1997; Gamon et al. 1995; Anderson et al. 1993). It has been used successfully to identify vegetation disturbance and stress, monitor restoration site establishment and the recovery of plant communities following disturbances, and scale-up in situ estimates of net annual primary production (Phinn et al. 1999; Steyer et al. 2013; All and Yool 2004; Hardisky et al. 1984; Ramsey et al. 1997; Couvillion and Beck 2013; Wang et al. 2010).

Remote sensing approaches have been used extensively to assess rates and identify causes of land loss in coastal Louisiana. Most previous studies have focused on land/water classification and changes in land area over time (Barras et al. 2003; Morton et al. 2005; Bernier et al. 2006; Couvillion et al. 2011; Fearnly et al. 2009), and quantifying and assessing patterns of land loss following hurricane events (Barras 2007a, 2009, 2007b; Palaseanu-Lovejoy et al. 2013). Remotely sensed imagery has also been used to identify geomorphic features associated with wetland erosion, deformation, and deposition following hurricanes (Morton and Barras 2011). Less attention has been given to changes in wetland health and productivity over time in coastal Louisiana. Most landscape-scale work on wetland productivity in coastal Louisiana has focused on using NDVI to assess the impact of hurricanes on coastal plant communities, including both forested wetlands (Ramsey et al. 1997; Ramsey et al. 1998; Ramsey et al. 2001; Faulkner et al. 2007) and coastal marshes (Steyer et al. 2013; Ramsey et al. 2012).

As a young, actively pro-grading delta, the Wax Lake Delta provides an ideal opportunity to study the development of deltaic plant communities and the factors that drive long-term trends and fluctuations in vegetative productivity in greater detail (Fig. 1). It is located in a region that experiences frequent coastal storm impacts, providing the opportunity to study the impact of storm disturbance on active deltaic marshes. On average, at least one hurricane or tropical storm strikes the Louisiana coast every other year. Since 1722, 35 hurricanes have had a significant morphological impact on Louisiana's coast (Stone et al. 1997). Averaged over the more than 100 years of record, the return interval of hurricanes with a rating of category 3 or greater is 26 years for the central Louisiana coast (Keim et al. 2007). As an actively accreting delta at the mouth of an unmanaged river diversion, the Wax Lake Delta provides an opportunity to study the resilience of deltaic wetlands with a direct connection to the river to coastal storm disturbance events.

The objectives of this study were (1) to determine the degree to which plant community production, as measured by NDVI, increases in a newly formed river delta over time, in concert with the geomorphological development of the delta and (2) to test whether coastal storm events have a lasting impact on long-term trends in plant community productivity.

Methods

Imagery Dataset

Long-term trends and storm event-driven fluctuations in the productivity of the vegetation community of the Wax Lake Delta were characterized using NDVI grids derived from Landsat Climate Data Record (CDR) surface reflectance imagery obtained from the US Geological Survey (USGS) Center for Earth Resource Observation and Science (EROS) (USGS 2014a, b). Landsat CDR products are higher-level Landsat products developed in accordance with guidelines established by the Global Climate Observation System to support assessment of land surface change over time. The original Landsat digital numbers are calibrated to at-sensor radiance and then atmospherically corrected to surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) software (Masek et al. 2006; USGS 2014a). LEDAPS applies atmospheric correction routines developed for Moderate Resolution Imaging Spectroradiometer (MODIS) imagery to Level-1 Landsat TM and ETM+ imagery. Second

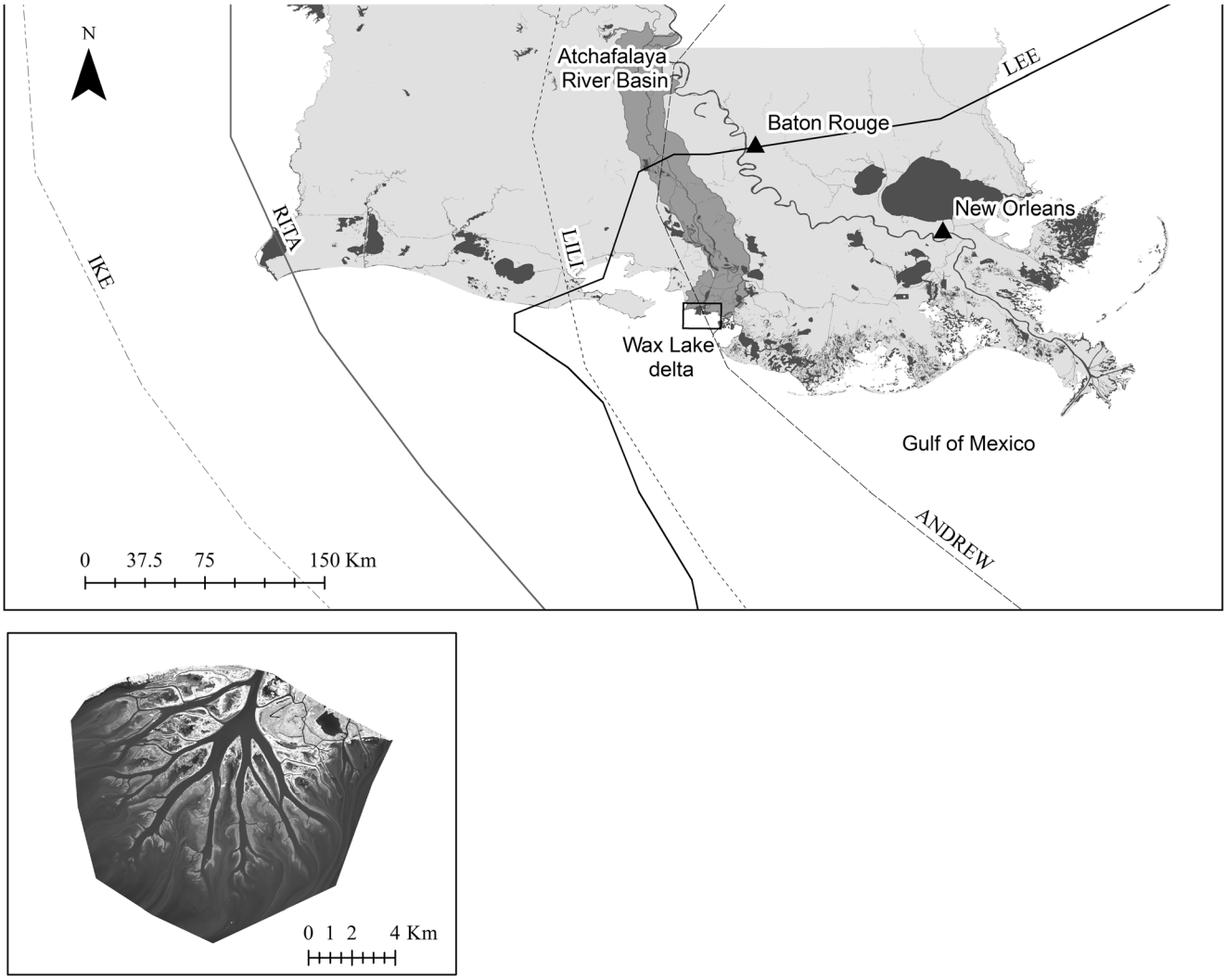

Fig. 1 Location of the Wax Lake Delta relative to storm tracks for the five storms influencing the vegetation community between 1984 and 2011

Simulation of a Satellite Signal in the Solar Spectrum (6S) radiative transfer models are run using Landsat data in combination with water vapor, ozone, geopotential height, aerosol optical thickness, and elevation data to generate top-of-atmosphere (TOA) reflectance, surface reflectance, brightness temperature, and masks for clouds, cloud shadows, adjacent clouds, land, and water (Vermote et al. 1997). Surface reflectance is then used to derive a number of spectral indices products, including the NDVI (USGS 2014b).

We selected 54 cloud-free, peak growing season (August–October) Landsat thematic mapper (TM) 4/5 and Landsat enhanced thematic mapper plus (ETM+) images of the Wax Lake Delta from 1984 to 2011 to use for this analysis (Online Supplemental Table 1). Only Landsat 7 ETM+ images collected with the scan line corrector operating (SLC-on, 1999-2003) were used for this study. Reflectance values and indices derived from the Landsat TM and ETM+ sensors have been demonstrated to be comparable when properly calibrated to the same radiometric scale (Masek et al. 2006; Vogelmann et al. 2001; Markham and Helder 2012; USGS 2014a). Because the S6 atmospheric correction technique used to obtain the Landsat CDR surface reflectance imagery is known to have lower accuracy in coastal areas with a high percentage of water compared to land area (USGS 2014a; Masek et al. 2006), we selected an image footprint containing the Wax Lake Delta that primarily included land, with a low percentage of water area (Worldwide Reference System-2 Path 23, Row 39; 30.3° latitude, −91.7° longitude).

Normalized Difference Vegetation Index

The NDVI is a weighted ratio of reflectance in the red and near-infrared (NIR) regions of the light spectrum and has been shown to correlate strongly with aboveground biomass, leaf area index, and chlorophyll content across a variety of ecosystems (Jensen et al. 2002; Dong et al. 2003; Paruelo et al. 1997;

Gamon et al. 1995; Box et al. 1989). It is calculated according to the formula (Rouse et al. 1974):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$$

Healthy vegetation absorbs light in the red region and strongly reflects light in the NIR region. This results in positive values of NDVI that increase with vegetation density and strength of photosynthetic activity. Water absorbs light most completely in the NIR region, resulting in negative NDVI values. Bare ground reflects light in both the red and NIR regions, resulting in NDVI values very close to zero. Strong relationships between NDVI and aboveground biomass and photosynthetic activity have been demonstrated in other coastal marsh settings (Drake 1976; Gamon et al. 1995; Gross et al. 1993; Hardisky et al. 1983; Nagler et al. 2009; White and Lewis 2011).

Both total vegetated area and spatially averaged NDVI (henceforth referred to as "mean NDVI") for the vegetated area of the delta were calculated using the Landsat CDR NDVI grids for each date in the time series. An NDVI threshold of 0 was used to separate the vegetated area of the delta from water. Water and any non-vegetated areas of the images were masked and the mean was computed for the NDVI values within the vegetated area using the ArcGIS Spatial Analyst zonal statistics tool (ESRI 2012). Total vegetated area was expected to not only increase as the delta prograded over time but also respond to seasonal fluctuations in water level. Mean NDVI measures the per unit area productivity of the delta and was expected to increase over time with plant community development and also to be inversely correlated to water level due to the dampening effect of flooding on NDVI values (Beget and Di Bella 2007). Both total vegetated area and mean NDVI were expected to respond to stress associated with storm disturbances.

Validation of Landsat NDVI Values

The Landsat 5 satellite was originally designed to operate for 3 years, with a possible extension for 5 years, but remained operational from its launch in 1984 until decommissioning in January 2013. Despite technical difficulties in the later years of its operation, it continued to provide high-quality thematic mapper imagery until the TM sensor failed in November 2011 (Markham and Helder 2012; Teillet et al. 2001; Markham et al. 2004; Thome et al. 2004; Wulder et al. 2011; Wulder et al. 2008). While the technical difficulties later in its operational life related to data transmission, power, and orbit positioning rather than the radiometric sensitivity of the TM sensor (Wulder et al. 2011), it is reasonable to question whether the radiometric quality of the imagery remained consistent in the final years of operation prior to sensor failure. While Thome et al. (2004) demonstrated that there was no apparent degradation of radiometric quality from 1995 to 2003, there is limited published validation of Landsat 5 TM image quality after 2003. To verify the reliability of the Landsat TM and ETM+ NDVI values used for this analysis during the final decade of Landsat 5's operation, we compared a subset of 9 cloud-free Landsat and same-day MODIS peak growing season NDVI images of the Wax Lake Delta from 2002 to 2011. The MODIS sensor has been validated more extensively than the Landsat sensors, and therefore, correlation with data derived from the MODIS sensor provides a good indicator of the reliability of the Landsat data (Feng et al. 2012). To account for the difference in spatial resolution between the two datasets, we averaged the NDVI values for the 30-m Landsat pixels that fell within each 500-m MODIS pixel. We then calculated the mean NDVI for both the resampled Landsat images and the MODIS images and compared the NDVI values from the two sensors using simple regression analysis.

Despite the small sample size, the validation results show a strong linear correlation between the resampled Landsat NDVI values and the MODIS NDVI values in the Wax Lake Delta during the peak growing season, with a correlation coefficient of 0.89 (Fig. 2). The regression model coefficients are similar to those presented for regression of simulated Landsat TM and MODIS data by Steven et al. (2003), particularly given that the current analysis was restricted to the peak growing season and all NDVI values measures were therefore at the high end of their annual range. Based on these findings, the Landsat TM CDR NDVI values were determined to be reliable measures of plant community productivity in the Wax Lake Delta.

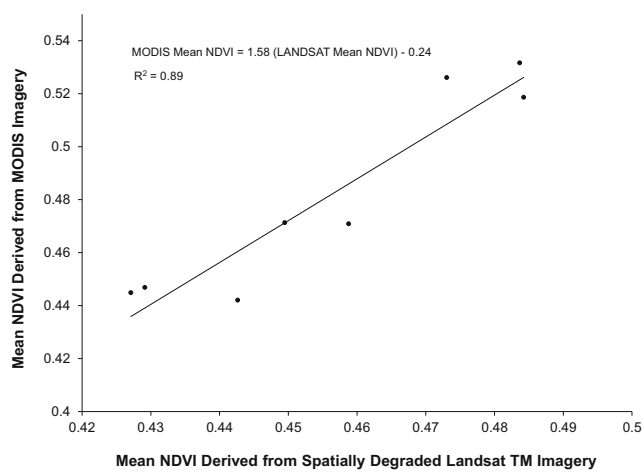

Fig. 2 Simple linear regression model for MODIS-derived mean peak growing season NDVI as a function of spatially degraded LANDSAT-derived mean peak growing season NDVI for the Wax Lake Delta from 2002 to 2010

Modeling Long-Term NDVI Trends

To control for variability in NDVI associated with seasonality and water level in the delta and identify long-term trends in peak growing season productivity, we developed multiple linear regression models for both vegetated delta area and mean NDVI for the period 1984 to 2011. Five potential explanatory variables were considered for each model: date, average growing season day, actual growing season day, river discharge, and tide level. Average growing season day was defined as the number of days since the date of the average last frost of the year as calculated for the Southern Regional Climate Center weather station in Morgan City, LA (www.srcc.lsu.edu). Actual growing season day was the number of days since the last frost as calculated from the same dataset and accounts for the fact that temperatures do not drop below freezing in southern Louisiana every year. Water level in the Wax Lake Delta (www.lacoast.gov/crms) varies as a function of both Atchafalaya River discharge (RiverGages.com) and tide level (www.tidesandcurrents.noaa.gov) (Fig. 3). As direct water level measurements are only available beginning in 2008 and there are continuous datasets for river discharge and tide level for the entire time period of interest, these two variables were considered in the NDVI models as proxies for water level. The best predictive model for both vegetated delta area and mean NDVI were selected by examining the set of all potential regression models ranging from simple linear regression models for each individual potential explanatory variable through a full model including all five explanatory variables and selecting the model with the highest adjusted r^2 value in which all variable coefficients were statistically significant at the 0.05 level and that best met the assumptions of the linear regression model.

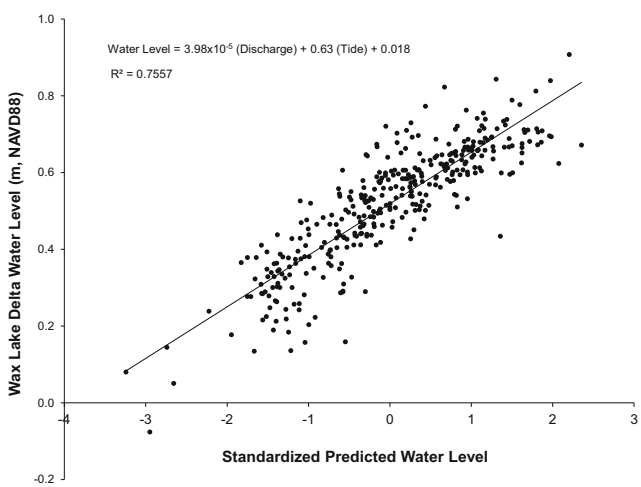

Fig. 3 Multiple linear regression model of Wax Lake Delta water level as a function of Atchafalaya River discharge and tide level for the year 2010. Water level data comes from the Louisiana Coastal Reference Monitoring System (CRMS) site in the Wax Lake Delta. River discharge data is from USACE Gage number 03045Q on the Atchafalaya River at Simmesport, LA. Tide level is from the NOAA tide gauge at Grand Isle, LA

Measuring Storm Disturbance and Recovery

Outlier analysis of the selected multiple regression models suggested that four images in the dataset were statistical outliers with respect to the long-term trend (standardized residuals less than −2). These images were each taken during the aftermath of one or more major storm events that affected coastal Louisiana: October 16, 2002 (Hurricane Lili), October 16, 2005 (Hurricanes Katrina and Rita), and September 22, 2008 and October 8, 2008 (Hurricanes Gustav and Ike). These data points were removed from the dataset used to calculate the long-term models. Two other storm events resulted in substantial decreases in both total vegetated area and mean NDVI in the delta that resulted in deviation from the long-term trend: Hurricane Andrew in 1992 and Tropical Storm Lee in 2011. While the standardized residuals for the images taken in the aftermath of these two storm events (October 12, 1992, September 15, 2011, October 1, 2011, and November 2, 2011) were not high enough to qualify as statistical outliers, outside evidence indicates that these events also had a substantial impact on the plant community in the delta (Barras 2007a,; M. Carle, personal observation). These data points were therefore also removed before re-calculating the models, so that the final models represent the long-term trends in total vegetated area and mean NDVI independent of short-term deviation associated with storm events. To further explore the impact of coastal storm disturbance on the vegetation community of the Wax Lake Delta, we identified all tropical storms and hurricanes in the Gulf of Mexico that passed within 400 km of the delta from the its emergence in 1973 to 2011 using the NOAA Historic Hurricane Tracks tool (http://csc.noaa.gov/hurricanes/#). Storms that approached the delta from the landward direction were excluded from the analysis. A storms dataset was created based on the characteristics of each storm when it passed closest to the delta, including storm category (tropical storm or category 1–5 hurricane), wind speed, pressure, distance from the Wax Lake Delta, direction of landfall relative to the Wax Lake Delta, and maximum storm surge. Storm surge was represented by the peak stage measurement at the USGS Wax Lake Outlet river gage in Calumet, LA (http://waterdata.usgs.gov/nwis/). Water level measurements were only available from 1997 to the present, preventing identification of storm surges associated with storm events prior to 1997. This dataset was used to identify the characteristics of historic storm events that impacted the vegetation community of the delta and differentiate them from storm events that did not disturb the vegetation community.

For four of the five storms that impacted the total vegetated area and mean NDVI in the delta, the post-storm standardized

residuals were compared to the standardized residuals for images taken during the following growing season to determine the resilience of the vegetation community following storm disturbance. This analysis was not performed for Tropical Storm Lee because failure of the Landsat 5 TM sensor in November 2011 prevented acquisition of a comparable representative image for peak growing season productivity in 2012. The area of impact for each of the five storms that affected the vegetation community in the delta was mapped based on the difference in vegetated area (NDVI >0) in Landsat images taken before and after the storm to identify the spatial extent and pattern of plant community disturbance.

Results

Total Vegetated Area Model

The best multiple regression model for total vegetated area included date and river discharge as significant explanatory variables. This model had a coefficient of determination (R^2) of 0.73. A simple linear regression model of total vegetated area as a function of date had a coefficient of determination of 0.70, suggesting that the inclusion of river discharge resulted in only a very slight improvement in the model. The standardized coefficient for the date variable was 0.85 compared to a standardized coefficient of −0.16 for the river discharge variable, further supporting that the growth in the delta over time has been the primary driver of the long-term trend in vegetated area. The equation for the selected multiple regression model is

$$\begin{aligned}&\text{Total Vegetated Area}\left(\text{km}^2\right)\\&= 0.0035(\text{SE} = 0.00)\text{Date(day)}\\&-0.002(\text{SE} = 0.001)\text{Discharge}\left(\text{m}^3\big/\text{s}\right)-493.22\\&\qquad n = 46, p = 0.00\end{aligned}$$

This model indicates that after controlling for river discharge, the total vegetated area of the Wax Lake Delta increased by 1.28 km^2 per year from 1984 to 2011. Discharge is negatively correlated with vegetated area, with a 1-km^2 decrease in measured total vegetated area associated with a 500 m^3/s increase in river discharge. Neither average growing season day nor actual growing season day were significant predictors of total vegetated area, either using simple linear regression or when considered as explanatory variables in multiple regression models. Tide level was also not a significant predictor of total vegetation area when discharge was also included in the model.

All linear regression models for total vegetated area that included date as an explanatory variable displayed moderate autocorrelation, likely related to the inclusion of NDVI values from several images within the same growing season. The Durbin-Watson statistic for the final model was 1.009, which is below the threshold of 1.48 indicating significant autocorrelation for a model with a sample size of 46 and two explanatory variables (Durbin and Warson 1950). This suggests that the model variance and confidence intervals for the regression coefficients may be underestimated and that an additional variable is likely needed in the model to account for the trend in the residuals. While autocorrelation in time series regression is often addressed with addition of a variable capturing seasonal variation, neither of the variables representing growing season day were significant in this instance. We therefore opted to accept the autocorrelated model for the purposes of identifying the long-term trend in total vegetated area and evaluating the impact of storm events, recognizing that the predictive strength of the model is lower than it would be were the autocorrelation to be removed through addition of a variable representing the seasonal trend in total vegetated area.

Mean NDVI Model

The best multiple regression model for mean NDVI included date and tide level as significant explanatory variables. This model had a coefficient of determination (R^2) of 0.69. A simple linear regression model of mean NDVI as a function of date had a coefficient of determination of 0.45, while a simple linear regression model as a function of tide level had a coefficient of determination of 0.51. In the multiple regression model, the standardized regression coefficients were 0.46 for date and 0.53 for tide level, suggesting that these two variables are equally important in explaining the trend in mean NDVI in the Wax Lake Delta from 1984 to 2011. The final multiple regression model for mean NDVI in the Wax Lake Delta was

$$\begin{aligned}\text{Mean NDVI} &= 1.90 \times 10^5(\text{SE} = 0.00)\text{Date(day)}\\&+ 0.33(\text{SE} = 0.057)\text{Tide Level(m)}\\&-2.44(\text{SE} = 0.57)\\&n = 46, p = 0.00\end{aligned}$$

This model suggests that after controlling for the influence of tide level, mean NDVI within the Wax Lake Delta increased by 0.007 per year from 1984 to 2011. There is a positive relationship between tide level and mean NDVI, with mean NDVI increasing 0.33 with a 1-m increase in tide level.

As with the total vegetated area model, neither average nor actual growing season day were important predictors of mean NDVI, either singularly or when combined with other variables in the multiple regression models. The final model for mean NDVI showed no significant autocorrelation, with a Durbin-Watson statistic of 1.80.

Storm Disturbance and Recovery

A total of 46 tropical storms and hurricanes passed within 400 km of the Wax Lake Delta in the Gulf of Mexico from 1973 to 2011 (Table 1). There was a large storm surge in the delta associated with each of the three storm events that resulted in significant impacts to the vegetation community: Hurricane Lili (2002), Hurricane Rita (2005), and Hurricane Ike (2008). Substantial storm surge was also measured in the Wax Lake Delta during Tropical Storm Lee in 2011. No water level data were available for Hurricane Andrew, which made landfall directly over the Wax Lake Delta in 1992. A common characteristic of all of the storms that impacted the plant community of the Wax Lake Delta was that they passed either to the west of or directly over the delta. No storms passing to the east of the delta had an observable impact on total vegetated area or mean NDVI. This includes several tropical storms that passed as little as 50 km east of the delta. All of the storms that impacted the plant community were category 2 hurricanes or greater, except for Tropical Storm Lee, which passed only 50 km to the west of the delta. Several of the storms impacting the delta made landfall far to the west of the delta. Hurricane Rita, a category 3 hurricane, made landfall near the Texas-Louisiana border in 2005, over 170 km from the Wax Lake Delta. Hurricane Ike, a category 2 hurricane, made landfall in Texas, over 270 km from the delta, but still resulted in a storm surge of over 1 m in the delta and a large decrease in both total vegetated area and mean NDVI following the storm.

Figures 4 and 5 illustrate how the total vegetated area and mean NDVI following these five storm events compare to the long-term trends as described by the multiple regression models. Both total vegetated area and mean NDVI decreased following each of these storms, with residuals greater than two standard deviations from the mean predicted value for all storms except for Hurricane Andrew in 1992 and Tropical Storm Lee in 2011. Hurricane Andrew is known to have resulted in substantial impacts to wetlands in the vicinity of its landfall near Morgan City, LA (Barras 2007a). However, Andrew made landfall on August 26, 1992, and the earliest available post-storm Landsat image is from October 12, 1992. It is probable that the vegetation in the Wax Lake Delta recovered substantially during the 6-week period between landfall and image acquisition, accounting for the limited storm effect that was observed. For Tropical Storm Lee, the September 15, 2011 and October 1, 2011 data points also most likely represents partial plant community recovery following the storm, which made landfall on September 3, 2011. Field observations made during the weeks prior to and immediately following the storm suggest that most of the vegetation at lower elevations was killed by salt burn (M. Carle, personal observation). The lower total vegetated area value on November 2, 2011 most likely represents the onset of senescence rather than the impact of the storm.

Hurricanes Lili (2002) and Ike (2008) had the largest spatial impacts on the plant community in the delta, as measured by the change in vegetated area (Fig. 6). Hurricanes Rita and Andrew had intermediate impacts, and the impact of Tropical Storm Lee was fairly small and limited to the lowest elevation areas of the delta in the interiors of the islands and along their distal fringe. Tables 2 and 3 compare the standardized residuals for total vegetated area and mean NDVI for the delta immediately after and 1 year following each influential storm event. In each case, the residuals for both total vegetated area and mean NDVI values for the year following the storm fell within 2 standard deviations of the predicted value from the multiple regression model, indicating that productivity within the delta had fully recovered from the storm disturbance.

Discussion

The regression models indicate that both total vegetated area and mean NDVI in the Wax Lake Delta increased substantially from 1984 to 2011. While river discharge was an important secondary driver influencing the vegetated area of the delta, most of the variability was explained by the long-term trend of increasing vegetated area over time concurrent with the growth of the deltaic platform itself. The early to mid-1980s are known to have been a time of rapid growth for the Wax Lake Delta (Allen et al. 2012). While the neighboring Atchafalaya Delta grew substantially following the floods in the 1970s, growth of the Wax Lake Delta lagged behind until the early 1980s (Roberts et al. 2003; Roberts et al. 1997). Prior to the early 1980s, river sediment was filling Wax Lake, a shallow natural basin located directly upstream of the mouth of the Wax Lake Outlet in the Atchafalaya Basin. Once Wax Lake was filled, sediment delivery to the delta increased substantially, leading to an increase in the growth rate of the delta (Roberts 1998). Consequently, the period from 1983 to 2002 was characterized by a rapid increase in the vegetated area of the delta. This is consistent with rapid vegetation growth that has been observed in other emergent river deltas (White 1993; Kandus and Malvárez 2004).

While a significant trend was observed over the entire time period from 1984 to 2011, the later years of the time period after 2002 are characterized by higher variability and a less clear trend than the earlier years. This may be an artifact of the fewer data points available to characterize the long-term trend from 2002 to 2011 due to the high number of hurricanes impacting the delta over that period. However, previous work suggests that the landfall of Hurricane Lili in 2002 may have initiated a new phase of stagnated growth for the delta. Morton and Barras (2011) documented the combined effects of Hurricane Lili and Tropical Storm Isadore on the central coast of Louisiana. Tropical Storm Isadore made landfall 8 days before Lili and caused widespread flooding in the marshes of coastal

Table 1 Hurricanes and tropical storms passing within 400 km of the Wax Lake Delta and their associated storm surge in the delta (for storms occurring after 1997)

Date	Storm name	Category	Wind speed (kts)	Pressure (mb)	Distance from WLD (km)	Direction relative to WLD	Surge above monthly mean water level (m)
9/4/1973	Delia	TS	60	993	266	West	–
9/8/1974	Carmen	3	105	937	11	Landfall at WLD	–
9/22/1975	Eloise	2	85	980	370	East	–
8/31/1977	Anita	1	75	986	321	South	–
9/5/1977	Babe	1	65	995	14	East	–
8/28/1978	Debra	TS	40	1002	199	West	–
7/11/1979	Bob	1	65	991	86	East	–
7/24/1979	Claudette	TS	35	1003	222	West	–
9/12/1979	Frederic	4	115	950	308	East	–
8/31/1979	Elena	TS	35	1004	293	West	–
9/11/1982	Chris	TS	50	1000	221	West	–
8/17/1983	Alicia	1	65	991	249	West	–
8/15/1985	Danny	1	80	988	120	West	–
9/2/1985	Elena	3	100	959	187	East	–
10/29/1985	Juan	1	65	974	9	Landfall at WLD	–
6/25/1986	Bonnie	1	65	1001	193	West	–
9/9/1988	Florence	1	65	985	144	East	–
6/26/1989	Allison	TS	35	1004	250	West	–
8/1/1989	Chantal	1	65	991	208	West	–
10/15/1989	Jerry	TS	60	991	334	West	–
8/26/1992	*Andrew*	*4*	*120*	*955*	*27*	*Landfall at WLD*	–
10/4/1995	Opal	4	130	919	359	East	–
7/17/1997	Danny	TS	50	1002	99	East	0.05
9/2/1998	Earl	TS	50	996	225	East	−0.02
9/27/1998	Georges	2	95	962	255	East	−0.07
9/20/1998	Hermine	TS	40	999	55	East	0.04
9/14/2002	Hanna	TS	50	1001	237	East	0.10
9/26/2002	Isadore	TS	55	989	112	East	−0.19
10/3/2002	*Lili*	*3*	*105*	*957*	*61*	*West*	*0.68*
6/30/2003	Bill	TS	50	997	53	East	0.00
7/14/2003	Claudette	TS	60	989	280	West	0.07
8/15/2003	Erika	TS	50	1001	379	West	−0.04
8/31/2003	Grace	TS	35	1008	354	West	0.18
8/11/2004	Bonnie	TS	55	1001	371	East	0.06
9/23/2004	Ivan	TS	50	998	90	west	0.26
10/10/2004	Matthew	TS	40	999	45	East	0.38
6/11/2005	Arlene	TS	60	993	377	East	−0.02
7/6/2005	Cindy	1	65	991	131	East	0.01
8/29/2005	Katrina	3	110	920	169	East	−0.13
9/24/2005	*Rita*	*3*	*105*	*931*	*171*	*West*	*1.31*
9/13/2007	Humberto	TS	55	997	208	West	0.23
8/5/2008	Eduoard	TS	50	999	106	West	0.23
9/1/2008	Gustav	2	90	954	26	East	0.13
9/12/2008	*Ike*	*2*	*95*	*954*	*272*	*West*	*1.05*
11/9/2009	Ida	1	65	990	267	East	0.11
9/3/2011	*Lee*	*TS*	*50*	*993*	*50*	*West*	*0.80*

Storms that impacted total vegetated area and mean NDVI in the delta are indicated in italic

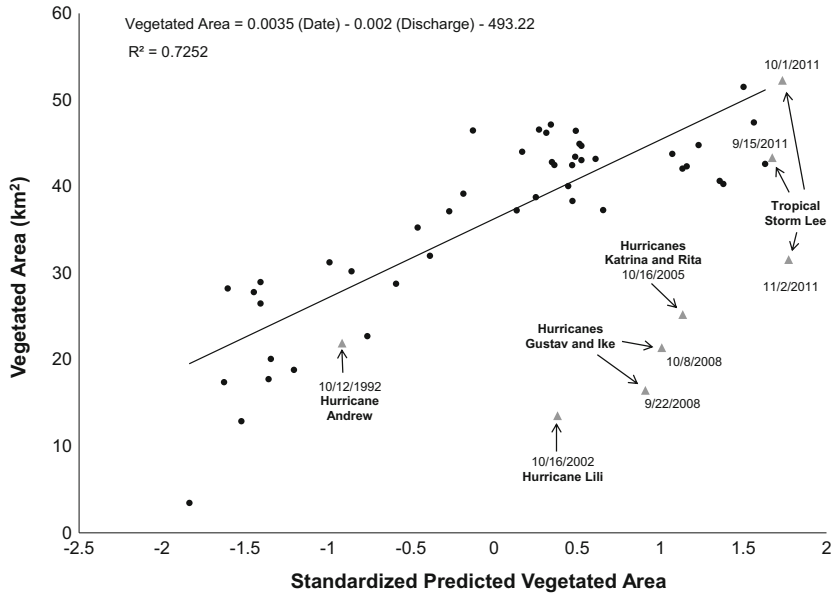

Fig. 4 Post-storm event vegetated area in relation to the long-term multiple regression model for vegetated area as a function of Atchafalaya River discharge and time from 1984 to 2011

Louisiana that had not fully receded when Lili hit. The impact of Hurricane Lili was greatest in the right front quadrant of the storm, where the storm formed elongated ponds in the marsh, expanded existing ponds, compressed the marsh surface, laterally displaced marsh mats up to 1 m thick, and eroded up to 70 m from the beaches of barrier islands (Morton and Barras 2011; Stone et al. 2003). Allen et al (2012) modeled land area change in the Wax Lake Delta as a function of time, river level, and tidal level from 1983 to 2010. They found a significant increase in the area of the delta from 1984 to 2002, but no significant relationship between delta area and time from 2002 to 2010. They suggest that disturbance by Hurricane Lili, combined with below average suspended sediment loads in the Atchafalaya River, explains the reduced growth rate of the delta during that time period. This explanation is supported by Rosen and Xu (2013) who found that net land loss in the Wax Lake and Atchafalaya Deltas from 1999 to 2004, which corresponded to a period without a major flood event and the highest storm surge event observed from 1989 to 2010 (Hurricane Lili).

Somewhat surprisingly, variables related to water level were not significant predictors of mean peak growing season NDVI in the Wax Lake Delta. While flooding can dampen NDVI values if reflectance from water is mixed with reflectance from vegetation in the same pixel, the dense vegetation canopy in the Wax Lake Delta appears to prevent a flooding effect in this case. The freshwater marsh communities in the Wax Lake Delta are dominated by dense floating and emergent vegetation, often with multiple layers of vegetation above the water surface. The strong reflectance of the vegetation

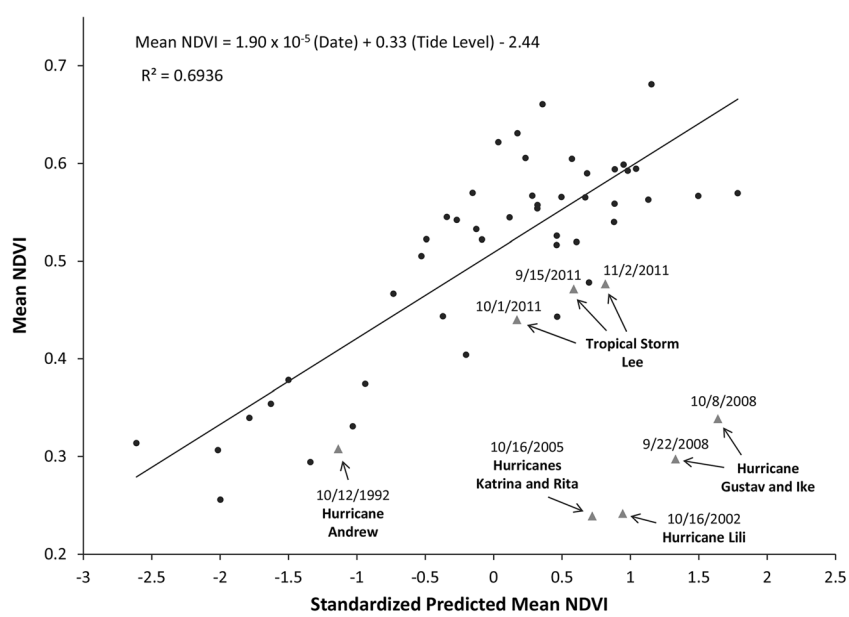

Fig. 5 Post-storm event mean NDVI in relation to the long-term multiple regression model for mean peak growing season NDVI as a function of tide level and time from 1984 to 2011

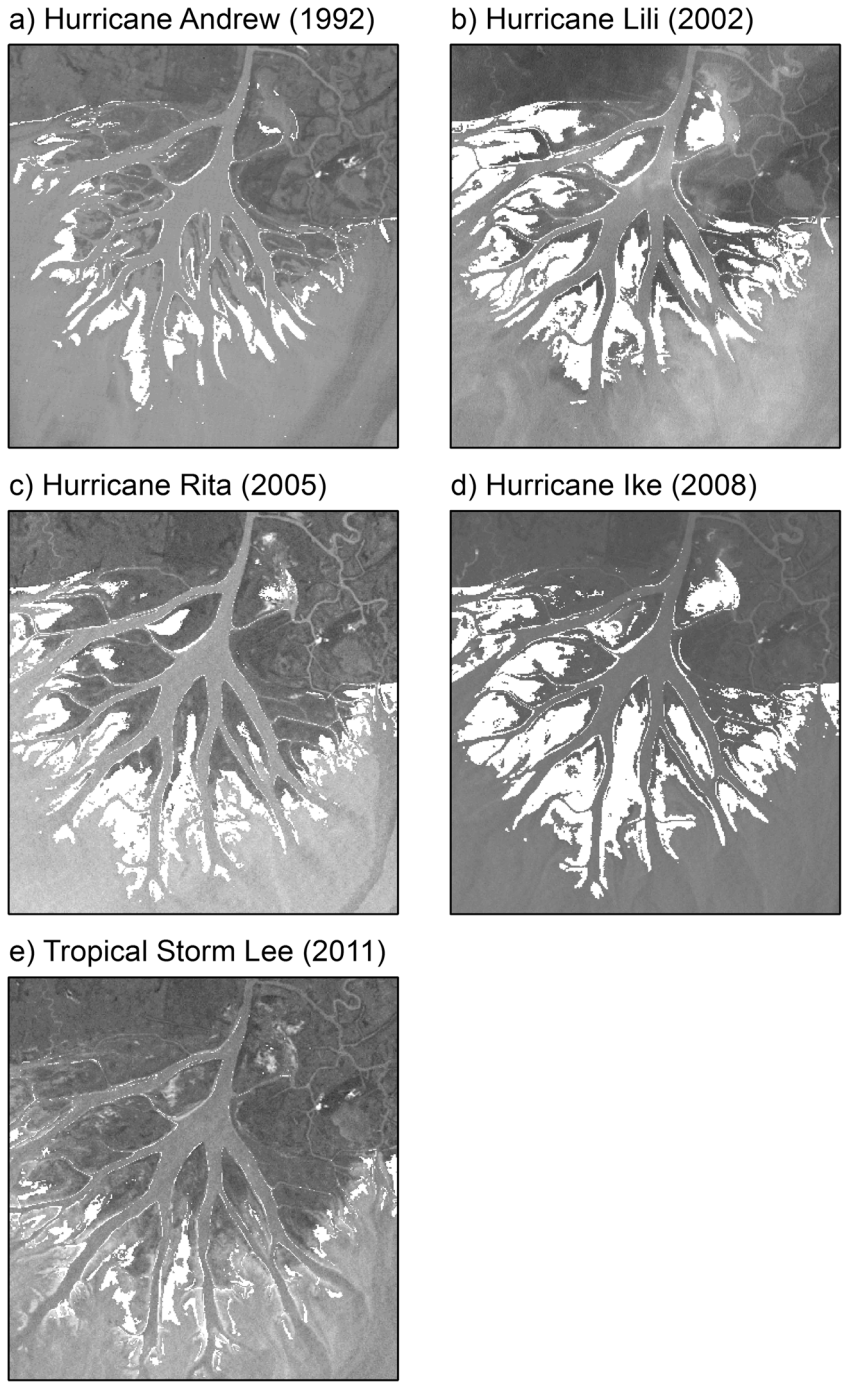

Fig. 6 Vegetation areas in the Wax Lake Delta impacted by Hurricanes Andrew (1992), Lili (2002), Rita (2005), Ike (2008), and Tropical Storm Lee (2011). *White* indicates areas that were vegetated prior to the storm event and unvegetated following the storm event

likely completely blocks reflectance from the water below. However, tide level was an important explanatory variable in the mean NDVI model, but the relationship between tide level and NDVI was the inverse of what would be expected as a result of the flooding dampening the NDVI values. The increase in mean NDVI with increased tide level explains as much variability in the regression model as the long-term increase in mean NDVI over time. We speculate that the observed relationship between tide level and NDVI is related to the benefit of tidal flushing for tidal freshwater marshes. Tidal exchange delivers sediment, nutrients, and oxygen to the marshes while removing waste products and other toxins (Odum et al. 1983; Whigham and Simpson 1992). While the marshes in the Wax Lake Delta should not be nutrient-limited due to a constant supply of nutrients from the Mississippi River (Turner and Rabelais 1991), the increase in oxygen supply and flushing of toxins associated with each tidal cycle may stimulate greater photosynthetic activity at high tide, which is then reflected in increased NDVI.

Table 2 Post-storm and post-recovery standardized residuals for vegetated area for four major hurricanes impacting the Wax Lake Delta in relation to the multiple regression model for vegetated area

Storm event	Image date	Post-storm standardized residual–mean NDVI	Image date	Following year standardized residual–mean NDVI
Hurricane Andrew	10/12/1992	−1.00	9/29/1993	0.77
Hurricane Lili	10/16/2002	−2.94	9/25/2003	0.66
Hurricane Rita	10/16/2005	−2.75	9/1/2006	1.18
Hurricane Ike	9/22/2008	−2.56	8/24/2009	0.53

The steady increase in mean NDVI throughout the study period is consistent with the successional development of the deltaic islands, as the low-growing colonizing annuals are replaced by perennial species that increase in biomass each year. While the emergent plants in the delta go dormant each winter, they contain significant underground stores and are capable of rapid regrowth in the spring. As elevations in the delta increase, the emergent plants are replaced by a much more species-rich mixed high marsh community. At these higher elevations, physical stressors are reduced and a greater range of species are able to colonize and more fully exploit all of the available resources. Vegetation cover is often much higher than 100 % in these areas (M. Carle, personal observation), with multiple layers of marsh plants exploiting every available niche in the canopy and understory. It is also common to find a layer of the vine *Vigna luteola* completely covering the marsh canopy. Thus, the geomorphic succession of the islands from newly emerged mudflats to higher elevation marshes is coupled with a process of ecological succession that leads to an increase in the per area productivity of the entire delta as measured by mean NDVI.

The recovery of the vegetation community within the Wax Lake Delta following each of the four major storm disturbances examined in this study supports the theory that the delivery of large amounts of sediment by a river to deltaic marshes instills a resilience in those marshes that is not seen when the same marshes are sediment-starved. Of the four hurricane events that impacted the delta, only Hurricane Lili had a potential long-term impact on the delta, and the impact of this storm event was most likely related to the lower than average sediment delivery that occurred in the years prior to the storm and a storm path that placed the Wax Lake Delta directly in the highest-impact right front quadrant of the storm (Allen et al. 2012; Rosen and Xu, 2013; Morton and Barras 2011). However, despite this combination of events, the vegetation community of the delta still recovered to within the 95 % prediction interval for the long-term trend by the following growing season.

It is worth comparing the impact of Hurricane Lili, a category 3 storm that made landfall just west of the Wax Lake Delta to that of Hurricane Andrew, which made landfall directly over the Wax Lake Delta in 1992. While similar impacts occurred to the marshes of the central Louisiana coast during Andrew as were observed following Lili (pond creation and elongation, marsh compression and dislocation), there was little widespread impact from this storm and much of the fresh and intermediate marshes around Atchafalaya Bay were observed to have completely recovered within 6 months following the storm (Morton and Barras 2011; Guntenspergen et al. 1995). This may have been related to the substantial amount of sediment that was deposited on the marsh surface as a result of the storm surge, with deposits up to 16 cm thick noted in some areas (Guntenspergen et al. 1995). Numerous studies have indicated the beneficial role that storm event sedimentation can have on coastal marshes in Louisiana (McKee and Cherry 2009; Williams 2012; Turner et al. 2006; Tweel and Turner 2012a; Nyman et al. 1995; Cahoon et al. 1995). The annual discharge and suspended sediment yield of the Atchafalaya River were also fairly high during the years prior to Hurricane Andrew, which may have increased the resilience of the delta's marshes during this time period (Rosen and Xu 2013). High sediment delivery to Atchafalaya Bay in the years preceding the storm also likely contributed to the high sedimentation rate associated with Andrew by providing a

Table 3 Post-storm and post-recovery standardized residuals for mean peak growing season NDVI for four major hurricanes impacting the Wax Lake Delta in relation to the multiple regression model for mean NDVI

Storm event	Image date	Post-storm standardized residual–vegetated area	Image date	Following year standardized residual–vegetated area
Hurricane Andrew	10/12/1992	−0.67	9/29/1993	0.87
Hurricane Lili	10/16/2002	−2.62	9/25/2003	−0.21
Hurricane Rita	10/16/2005	−2.11	9/1/2006	−0.58
Hurricane Ike	9/22/2008	−2.52	8/24/2009	−0.38

nearshore source of sediment that could be re-worked onshore by the storm surge, mitigating the overall negative impact of the storm on the marshes in this region.

In general, the influence of tropical storms and hurricanes on the plant community of the Wax Lake Delta appears to be limited to those that make landfall to the west of delta, which force a strong surge of saltwater into the delta that burns the vegetation and initiates a short-term die-off event. Even hurricanes that make landfall over 150 km to the west of the delta can still result in large storm surges and short-term impacts to the plant community, as exemplified by Hurricane Rita in 2005 and Hurricane Ike in 2008. When storms occur late in the growing season, plant community productivity may not fully recover until the following growing season. However, for storms that occur early in the growing season, the plant community may experience at least partial recovery before seasonal senescence occurs. This appears to have been the case following Tropical Storm Lee in 2011.

Our analysis of storm impacts was limited to storms for which cloud-free growing season images were available for before and after the storm event and for the growing season following the storm. Unfortunately, there were far fewer usable images for the earlier years of the Wax Lake delta's development, so it is uncertain which storms prior to 1992 impacted the vegetation community. The water level record is also incomplete, making it impossible to assess the extent of storm surge associated with storm events prior to 1997. However, based on their similarity to the more recent influential storms, Hurricane Carmen (1974), Hurricane Babe (1977), and Hurricane Juan (1985) likely had at least some short-term impact on marsh productivity in the delta. Hurricane Carmen was a category 3 storm that passed directly over the Wax Lake delta. However, as this storm occurred only a year after the first mudflats began to emerge in the Wax Lake delta, its impact was probably minor. The same is likely true of Hurricane Babe, which was a category 1 storm when it made landfall just to the east of the newly formed delta. Hurricane Juan was also a category 1 storm, but occurred in 1985, after the subareal part of the delta had begun to grow rapidly and when the plant community was more well-established. We predict that this storm had a similar effect as Tropical Storm Lee, causing minor salt burn in the lowest elevation communities, with complete recovery by the following year.

Overall, the results of this study suggest that the marshes of the Wax Lake Delta demonstrate considerable resilience to storm impacts, compared to what has been documented for other wetlands in the Mississippi River deltaic plain. Steyer et al (2013) used NDVI to assess the impact and recovery of marshes throughout coastal Louisiana following Hurricanes Katrina and Rita in 2005. They found that below average values of NDVI persisted in most marsh communities 1 year following the storms, but that these persistent impacts were concentrated in the east and the western regions of the state, where the two storms had the most direct impact. Very little persistent impact from the storm events was observed in the central region, which includes Atchafalaya Bay (Steyer et al. 2010). The impact of Hurricane Rita was particularly strong in southwestern Louisiana, where marshes were subjected both to higher direct physical disturbance and ponding of saltwater which was trapped in the marshes following the storm (Steyer et al. 2010). This resulted in greater long-term impacts to these marshes than in the central coastal region. In the case of the Wax Lake delta, the high flow of freshwater through the delta likely flushes salt from the soil quickly following such storm surge events, preventing long-term increases in pore water salinity and consequent impacts to the vegetation. A similar rapid recovery was observed in the marshes in the Mississippi River delta following Hurricane Camille (Chabreck and Palmisano 1973).

Conclusions

This study demonstrated that the marshes in the Wax Lake delta, a small, pro-grading delta formed at the mouth of an artificial diversion of the Mississippi River, have rapidly increased in both areal extent and mean productivity over the life of the delta. This trend of increasing productivity stands in sharp contrast to the long-term decrease in productivity occurring throughout the wetlands in the greater Mississippi River delta plain (Cardoch et al. 2002). As such, it illustrates the positive impact on deltaic marsh productivity provided by a direct connection to the river and the tremendous volume of freshwater and sediments that it provides. This connection with the river has resulted in an increase in both vegetated area and mean NDVI as the deltaic platform has accreted vertically and laterally since the early 1980s. The increase in vegetated area related to colonization of the expanding deltaic platform. The increase in mean NDVI can be attributed to plant community successional processes by which early colonizing annuals are gradually replaced by perennial species that increase in biomass each year and by the more complete utilization of available resources as elevations within the delta increase and a wider variety of plant species are able to colonize.

In the Wax Lake delta, the Mississippi River has built deltaic marshes that not only are increasing in productivity over time, but also demonstrate remarkable resilience to coastal storm disturbance. While long-term hurricane impacts are evident in marshes throughout coastal Louisiana, the marshes of the Wax Lake Delta show no signs of long-term physical disturbance following storm events. Strong storms passing to the west of the delta are capable of producing substantial short-term disturbance, predominantly by producing large storm surges that carry saltwater into the normally freshwater environment. This results in a temporary decrease in

productivity with full recovery by the following growing season. Such rapid recovery of plant community productivity occurred even following Hurricanes Andrew and Lili, two very strong storms that passed just to the west of the delta, placing the deltaic marshes directly in the most heavily impacted front right quadrant of the storm. The high freshwater flows through the Wax Lake Outlet most likely prevent any long-term increases in pore water salinity in the delta. There was also no evidence in the Wax Lake Delta of direct erosion to open water or marsh compression and dislocation, as has been observed in other coastal marshes in Louisiana following large storm events (Morton and Barras 2011).

Overall, the evidence provided by our analysis of NDVI trends in the Wax Lake Delta suggests that these marshes are productive systems that are continuing to increase in productivity over time and demonstrate considerable resilience to coastal storm disturbance. As the Wax Lake Outlet is essentially an unmanaged river diversion, the results of this work have important implications for the potential success of other large-scale river diversions that have been proposed to build and restore marshes elsewhere in coastal Louisiana (Coastal Protection and Restoration Authority (CPRA) 2012). Our observations at the Wax Lake Delta suggest that restoring the connection between deltaic marshes and the river that built them should help to increase both the productivity and resilience of deteriorating marsh communities elsewhere in the Mississippi River deltaic plain.

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