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Article

Potential of MODIS EVI in Identifying Hurricane Disturbance to Coastal Vegetation in the Northern Gulf of Mexico

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Abstract: Frequent hurricane landfalls along the northern Gulf of Mexico, in addition to causing immediate damage to vegetation, also have long term effects on coastal ecosystem structure and function. This study investigated the utility of using time series enhanced vegetation index (EVI) imagery composited in MODIS product MOD13Q1 for assessing hurricane damage to vegetation and its recovery. Vegetation in four US coastal states disturbed by five hurricanes between 2002 and 2008 were explored by change imagery derived from pre- and post-hurricane EVI data. Interpretation of the EVI changes within months and between years distinguished a clear disturbance pattern caused by Hurricanes Katrina and Rita in 2005, and a recovering trend of the vegetation between 2005 and 2008, particularly within the 100 km coastal zone. However, for Hurricanes Gustav, Ike, and Lili, the disturbance pattern which varied by the change imagery were not noticeable in some images due to lighter vegetation damage. The EVI pre- and post-hurricane differences between two adjacent years and around one month after hurricane disturbance provided the most likely damage area and patterns. The study also revealed that as hurricanes damaged vegetation in some coastal areas, strong precipitation associated with these storms may benefit growth of vegetation in other areas. Overall, the study illustrated that the MODIS product could be employed to detect severe hurricane damage to vegetation, monitor vegetation recovery dynamics, and assess benefits of hurricanes to vegetation.

Keywords: MODIS; enhanced vegetation index; hurricane; forests; wetlands; Northern Gulf of Mexico

1. Introduction

Historically, about 10.6 major hurricanes with Saffir-Simpson scales greater than 2 have made their landfalls along the northern Gulf of Mexico each decade from 1896 to 1995 [1]. Between 2002 and 2008 five hurricanes, particularly Katrina in 2005, have devastated the Gulf Coast region with hurricane winds frequently uprooting trees and snapping stems with enormous economic loss to the wood industry. For instance, Hurricanes Katrina and Rita in 2005 damaged about 4.4 billion board feet of sawtimber inventory in Louisiana, which were equivalent to more than two years' worth of pine sawtimber harvest and more than 11 years' worth of hardwood sawtimber harvest for the entire state [2]. Besides wind damage, the salty water intrusion into coastal wetlands and even inland areas usually temporarily destroy existing marsh vegetation. However, the sediments delivered by the storm surges while burying or removing vegetation can also contribute to overall marsh rebuilding [3]. The level of devastation exerted by a hurricane on the vegetation are related to a complex set of biotic and abiotic factors, such as vegetation attributes and site conditions, as well as hurricane wind speed and direction. For example, the severity and spatial patterns of Katrina disturbance to forests in southeastern Louisiana were mainly determined by soil properties, forest types, forest coverage and stand density [4]. In coastal wetlands, the salinity level following hurricane disturbance is a crucial factor in determining the specific effects of a storm on coastal vegetation [3]. Entrapment of saline flood waters could exert a more extensive and long-term damage to marshes, while natural, free-draining marsh areas generally suffer little damage [5].

Although hurricanes cause severe damage to natural resources, vegetation including both forests and marshes often display quick recovery in terms of new leaf sprouts and productivity increases the following years. The percentage of total coverage of natural marshes can return to pre-storm conditions within approximately one year after the storm events, although several species change were evident [5]. In about a month after Katrina's landfall, both the bottomland forests and cypress forests displayed substantial recovery in forest foliage but cypress forest recovery was more dramatic than that of bottomland forests [6]. Sediments delivered by Katrina may have stimulated a 10-fold increase in belowground productivity of brackish marshes in the Mississippi River deltaic plain [7]. The massive input of plant detritus to soil may have contributed to significant increases of N mineralization rate and an average increase of 30% annual gross primary productivity of forest at low elevation land within five years after Hurricane Hugo disturbance [8]. After Hurricane Georges passed over the Dominican Republic in 1998, mangrove forest understory light levels increased from an average value of three percent in the pre-hurricane forest to 51 percent seven months after the hurricane, which may have contributed to the rapid population recovery of seedling and sapling of the mangroves [9]. In the recovery of the tropical forests from hurricane damage, rapid resprouting of damaged trees, particularly primary forest species, play a major role [10,11]. Strong wind and storm events may promote healthier communities because they could redistribute sediments and biological seed material, as well as remove accumulated toxins [12].

Immediate damage of hurricanes to vegetation and recovery starting from weeks to months after the disturbance draw a dynamic picture of the vegetation coverage. Assessment of the immediate damage and monitoring of the long period of vegetation recovery are vital for resource managers and scientists to take short term actions to salvage harvesting and habitat protection, as well as to evaluate the long-term forest ecosystem recovery and wetland restoration. In situations where hurricane disturbance are spread over a larger area and the disturbed vegetation have variable recovery rates, the use of remote sensing is well suited for assessing and monitoring vegetation dynamics [6,13-18]. Wang and Xu [14] compared performance of four change detection algorithms with six vegetation indices derived from pre- and post-Katrina Landsat Thematic Mapper (TM) imagery and a composite of the TM bands 4, 5, and 3 in identifying Katrina's damage to forests. The authors concluded that the highest accuracy was achieved by the application of post classification comparison algorithm to the composite image. Ramsey *et al.* [6,16] studied Hurricanes Katrina and Andrew disturbance to forests in coastal Louisiana with radar and NDVI images derived from Landsat, and found some forest recovery after a month of the disturbance. Nielsen [18] demonstrated the use of the 250-m daily reflectance product (MOD09GQK) and the aggregated Landsat TM damage data to rapidly map hurricane Katrina disturbance to forests.

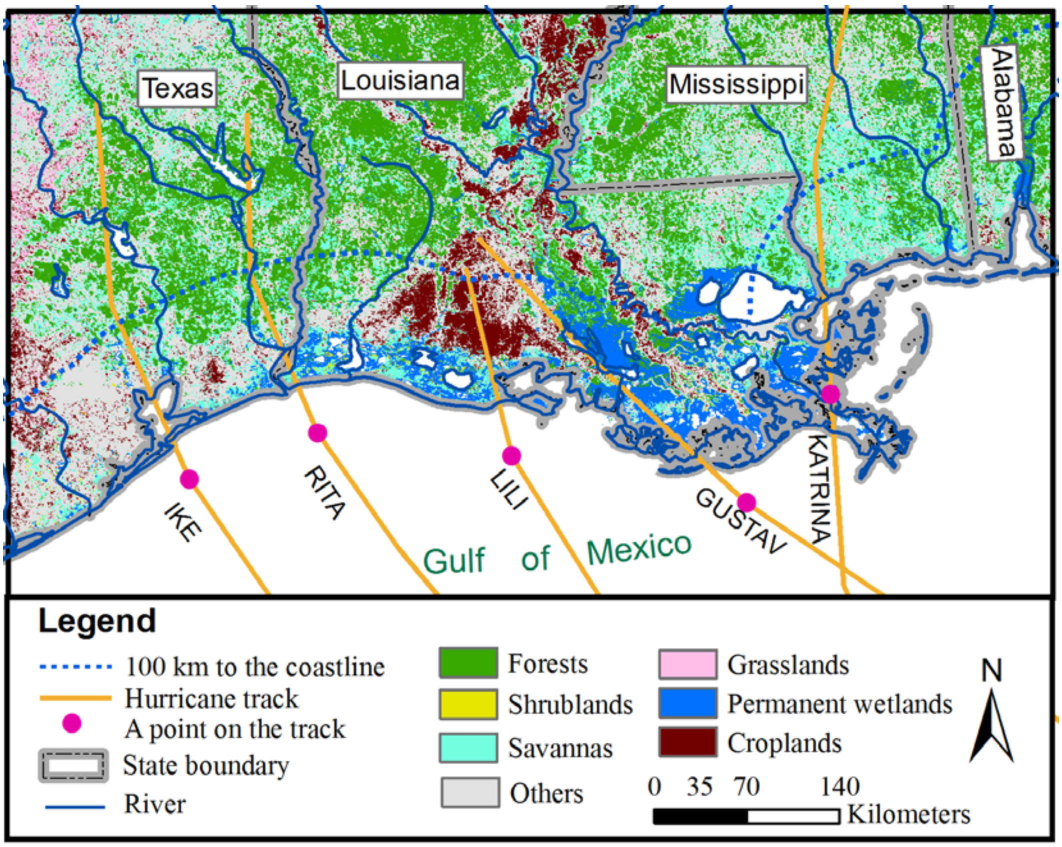
Collectively, these studies mainly employed vegetation index images on two dates, one pre- and one post-hurricane event, along with change detection algorithm such as image differencing to generate change imagery. Then the imagery were trained with ground truth data or other reference data to identify the disturbances. The damage identified by this approach revealed the vegetation condition on the specific date. Yet vegetation dynamics involving both damage and recovery from weeks to months, and even years were not investigated. Thus owing to different types of damage to vegetation, such as uprooted trees, snapped stems, salt burn, and even over wash marsh grass, as well as divergent phases of vegetation recovery spanning weeks to years, a time series of vegetation index images such as MODIS vegetation index product is well suited to investigate vegetation changes after the disturbance. The products are designed for precise seasonal and interannual monitoring of vegetation activity in support of phenologic, change detection, and biophysical interpretations [19]. The vegetation index products are available at five spatial resolutions and at 16-day and monthly intervals starting February 2000. An unique product, the EVI is directly derived from the daily reflectance product over a 16 day period by two algorithms [19]. The performance of the EVI product in identifying hurricane disturbance and vegetation recovery is not clear. Therefore, the purpose of our study was to visualize general trends and to investigate applicability of the MODIS EVI products for assessing the hurricane damage to vegetation and monitoring the vegetation recovery at landscape level. We hypothesize that a noticeable negative change of the vegetation index values due to hurricanes is expected. The decline of EVI values should be caused by forest defoliation and canopy coverage loss, as well as damage of salt burn and scouring from hurricane storm surges on marsh vegetation. On the other hand, a positive change would represent a recovery of the vegetation, such as marsh grass regrowth and forest sprouting. In addition, owing to divergent susceptibility of vegetation to hurricane damage and various recovery phases, we also hypothesize that only EVI on a certain date can to a great extent represent the signature of hurricane damage to vegetation.

2. Methods

2.1. Study Area

The study area comprises large parts of the four US states bordering the Gulf of Mexico: Texas, Louisiana, Mississippi, and Alabama, with a focus on coastal zone within 100 km from the coastline (Figure 1). Geographically, the area is located between longitude 96° W and 88° W, and between latitude 28° N and 32° N. With major river systems such as the Mississippi River, Atchafalaya River, and Sabine River draining into the northern Gulf of Mexico, the fresh water discharge from the rivers have a significant impact on the coastal physicochemical characteristics and biological communities [12]. The Gulf Coast is featured by barrier islands developed by long shore transport and deposition of sands, and the deltas and plains deposited by deltaic and plume transport processes of the rivers [12]. The coastal marshes and swamps play a critical role in improving water quality, controlling floods and erosion, buffering storm surges, and providing habitats for fish and wildlife. The coastal region also supports a strong local and national economy through commercial and sport fishing, petrochemical and wood industry, agriculture, tourism, and cargo transportation.

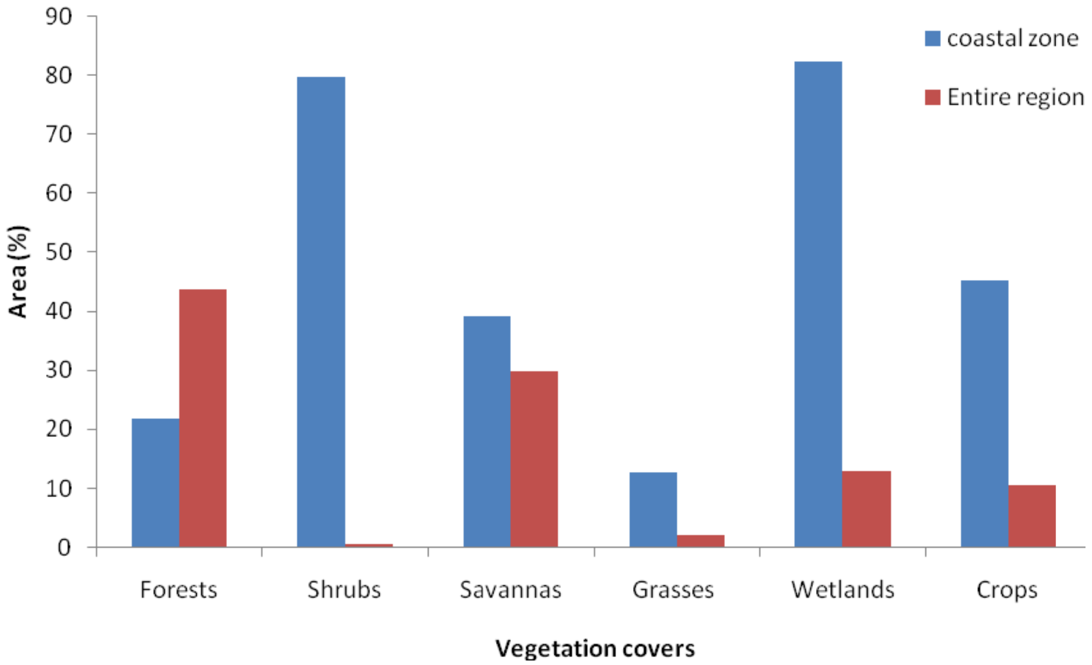
Figure 1. Distribution of main vegetation groups in northern Gulf of Mexico and landfalls of hurricanes between 2002 and 2008.



Vegetation in this region consists of 14 types as shown by MODIS land use land cover product MCD13Q1, which classified land covers according to classification scheme of the International Geosphere-Biosphere Programme (IGBP). After aggregating the 14 types to six broad groups, forests and savannas were found to cover two-thirds of the area and distributed mainly in inland terrain

(Figures 1 and 2). The main species group in upland forests comprise of loblolly-shortleaf pine, longleaf-slash pine and oak-pine groups. The bottomland hardwoods are predominantly oak, hickory, elm, ash, and sweetgum. Crop land with one-tenth coverage is mainly clustered in Louisiana and Texas. The crop rotation may bring more uncertainties as we compare changes in multi-year vegetation index values. Therefore, hurricane disturbance to crops were not assessed in this study. In the coastal zone within 100 km of the coastline, wetlands and shrubs are the main vegetation types with 80% distribution as compared to about 20% coverage in the remaining region. The dominant brackish and salt marsh vegetation species consist of black needle rush, saltmeadow cordgrass, and salt marsh cordgrass [12]. Vegetation in the region is vital for local economic development, wildlife refuge, and coastal protection.

Figure 2. Area percentage of the vegetation covers in the entire region (red bars) and percentage fraction of vegetation covers in the coastal zone within 100 km from the coastline to that over the entire study area (blue bars).



Frequent hurricanes in the northern Gulf of Mexico have exposed the Gulf Coast states to frequent strong winds and storm surges. For example, from 2002 to 2008, five hurricanes made landfall in the study region (Table 1) with Hurricane Katrina, the third strongest storm during the last 100 years to make landfall in the US on 29 August 2005 near the Louisiana-Mississippi border. With sustained winds of 195 km/h hour and a storm surge level up to 7 m, the hurricane caused catastrophic damage in the coastal region and loss of at least 1,836 lives mainly due to levee breaking around the city of New Orleans. Damage assessment due to Hurricanes Katrina and Rita (another hurricane that made landfall along the Louisiana-Texas coast on 24 September 2005) to forests, wetlands, and entire ecosystem have been extensively conducted by various government agencies and research communities [3,14,20-24]. Hurricanes Gustav and Ike which struck the Gulf region in 2008 did not cause as severe a damage as Hurricane Katrina as the upgrades and repairs to the New Orleans area levee system successfully withstood the rising waters brought by Hurricane Gustav [25]. However, the hurricanes still severely disturbed vegetation in the coastal states [7,26].

Table 1 Characteristics of hurricanes that struck the northern Gulf of Mexico during 2002–2008[a].

Name	Year	Month	Day	Local Time	Lat (°)	Lon (°)	Wind (km/h)	Pressure (Millibars)	Category
Lili	2002	10	3	6:00AM	29.2	−92.1	148	962	H1
Katrina	2005	8	29	6:00AM	29.5	−89.6	204	923	H3
Rita	2005	9	24	12:00AM	29.4	−93.6	185	935	H3
Gustav	2008	9	1	6:00AM	28.8	−90.3	176	955	H2
Ike	2008	9	13	12:00AM	29.1	−94.6	176	951	H2

Note: [a] Characteristics at the locations represented by red dots in Figure 1.

2.2. Disturbance Detection with MODIS EVI

MODIS vegetation index product MOD13Q1 was applied in this study to identify hurricane disturbance to vegetation. The MOD13Q1 product is a composite of eight layers including NDVI, EVI, and reflectance at red, near-infrared, and blue wavelength. EVI is computed from MODIS red, near-infrared (nir), and blue bands using the equation:

$$EVI = 2 \times \frac{(\rho_{nir} - \rho_{red})}{(L + \rho_{nir} + C_1\rho_{red} + C_2\rho_{blue})} \quad (1)$$

where ρ is surface directional reflectance, L is a canopy background adjustment term, and C_1 and C_2 weigh the use of the blue channel in aerosol correction of the red channel [19]. For EVI, the 500m blue band is used to correct for residual atmospheric effects due to the absence of 250m blue band, with negligible spatial artifacts. The reflectance for computing EVI at 16-day compositing period and 250 m spatial resolution is selected by two algorithms. The first algorithm fits the Walthall bidirectional reflectance distribution function (BRDF) model to the individual band data when a minimum of 5 surface reflectance observations are available within the 16 days. If no more than 5 cloud-free data points are available during the period, then a back-up algorithm is used. The approach selects the highest NDVI value for the final product from two cloud free pixels with their view angles closest to nadir. EVI compositing procedures and quality control are described in Huete *et al.* [19].

For this study area, four tiles of the MODIS product image (h9/v5, h9/v6, h10/v5, and h10/v6) are required to cover the entire region. The tiles from July through November between 2000 and 2008 were downloaded via the Data Pool Tool supplied by the USGS Land Processes Distributed Active Archive Center (LP DAAC). The tiles were then reprojected from Sinusoidal to Albers Equal Area projection and mosaicked into one image with MODIS Reprojection tool. The change imagery ($EVI\ change_{i,i+16,j}$ and $EVI\ change_{i,j,j+1}$) were computed using the equations:

$$EVI\ change_{i,i+16,j} = \frac{(EVI_{i+16,j} - EVI_{i,j})}{EVI_{i,j}} \times 100 \quad (2)$$

$$EVI\ change_{i,j,j+1} = \frac{(EVI_{i,j+1} - EVI_{i,j})}{EVI_{i,j}} \times 100 \quad (3)$$

where *i* is the day number and *j* the year of the EVI product. The first equation was employed for computing changes between two dates within a year while the second was used for calculating the percentage difference for the same day between two adjacent years. After generation of the change imagery, an image with 45% reduction in the EVI values was extracted from it for representing the immediate damage as suggested by Rodgers [28]. The author demonstrated that the 49% decrease in NDVI from March 24, 2005 to September 16, 2005 was most likely caused by hurricane Katrina and the values were still 44% lower in 2006 as compared to 2005. In addition, we visually compared the disturbance image with the hurricane disturbance in Lower Pearl River Valley in southeast Louisiana and south Mississippi identified by Wang and Xu [14], and found the disturbance image with greater than 45% reduction of the EVI values pre- and post-hurricane displayed a similar disturbance pattern. For monitoring the long-term vegetation dynamics, the change images were classified into eight categories, and vegetation areas in the coastal zone by the categories were computed. The spatial pattern and area changes were investigated for assessing how the hurricane disturbance impacts the vegetation coverage. All image manipulation and data visualization were conducted in ERDAS Imagine 9.3 and ArcGIS 9.3.

3. Results

3.1. Disturbance Detection by EVI Changes within Months

The spatial distribution and temporal variation of images showing greater than 45% decline in MODIS EVI values from pre- to post-hurricanes presented divergent trends of vegetation disturbance to hurricanes (Figure 3). As compared to pre-hurricane EVI changes on September 13 and 29, 2004 (Figures 3a,c), Hurricane Katrina apparently damaged forests and savannas as indicated by the red polygons on the images (Figures 3b,d). Hurricane Rita obviously disturbed the coastal swamps and marshes as labeled by the green polygons (Figures 3d,f) as compared to the situation in 2004 (Figures 3c,e). Moreover, the damage labeled by the green polygon on the right could be from both Katrina and Rita. As compared to the normal variations of the vegetation index (Figure 4a), upland forests in central Louisiana and wetland forests and marshes in southeast coast of the state labeled as red polygons could have been disturbed by Hurricane Gustav (Figure 4b). The damage to vegetation by Ike was not identified from the images on September 29 and October 16 (Figures 4c–4f). Hurricane Lili, which struck the Louisiana coast in 2002, could have disturbed upland forests in central Louisiana (Figure 5). However, the EVI value changes were not sufficient to reveal noticeable damage from Hurricane Lili to wetlands across the wind swath.

The vegetation area with greater than 45% decline of the EVI values in the entire region (Figure 6) revealed that for Katrina, Rita, and Lili, the areas following the events were greater than the areas without hurricane disturbance, indicating a hurricane disturbance to vegetation. However, following Hurricane Gustav, the vegetation area 13 days after the disturbance was higher than the reference area. Thus following Hurricanes Gustav and Ike landfalls, the disturbance areas on September 29 and October 15 were unexplainably lower than those under normal conditions.

Figure 3. Greater than 45% decrease of the MODIS EVI values between two dates in the same year as shown on the maps. The images on the left column as references, display the changes without hurricane disturbance. The maps on the right column represent the changes after Hurricane Katrina and Rita disturbance.

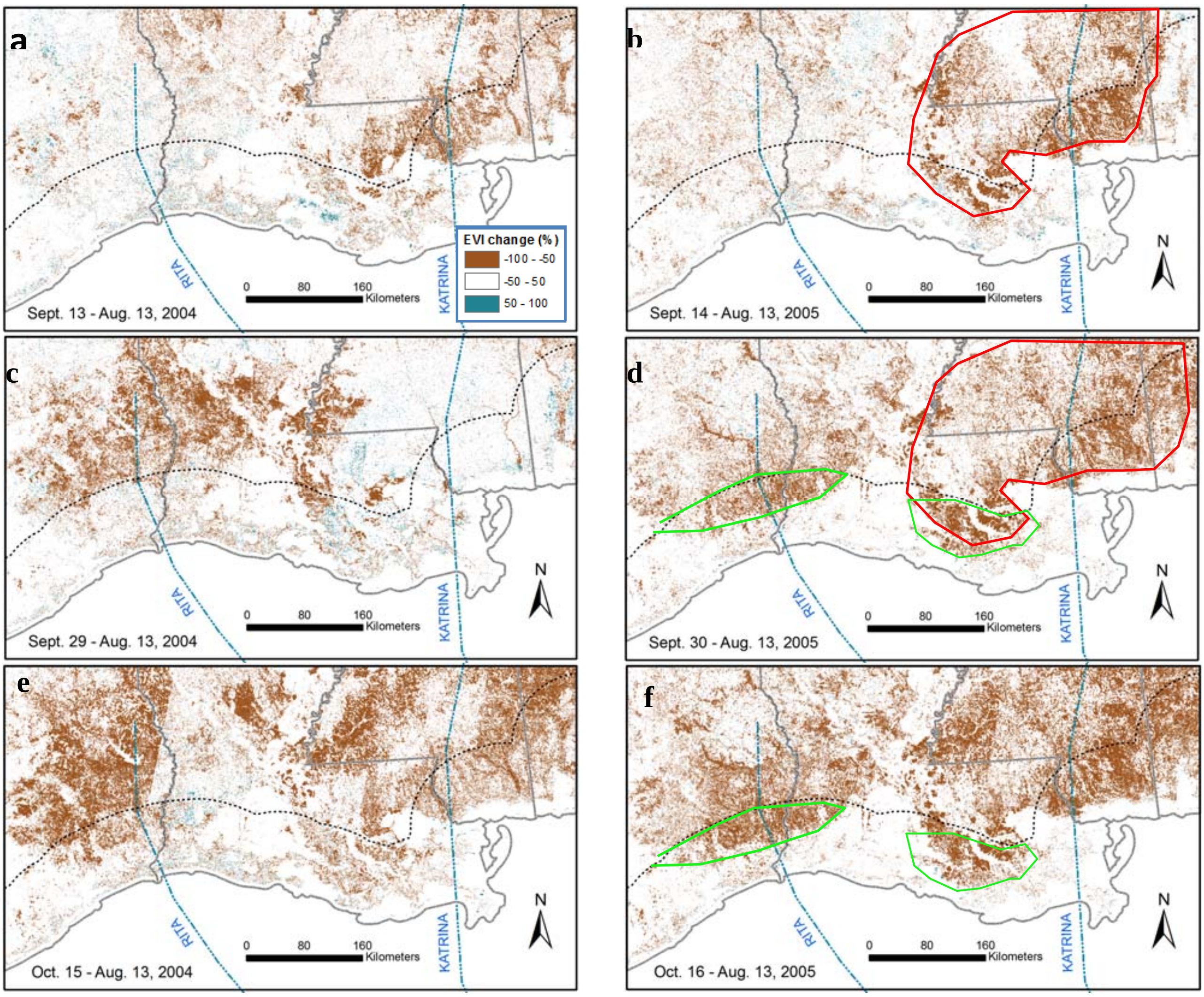


Figure 4. Greater than 45% decrease of the MODIS EVI values between two dates as shown on the maps. The images on the left column as references, display the changes without hurricane disturbance. The maps on the right column represent the changes after Hurricanes Gustav and Ike disturbance.

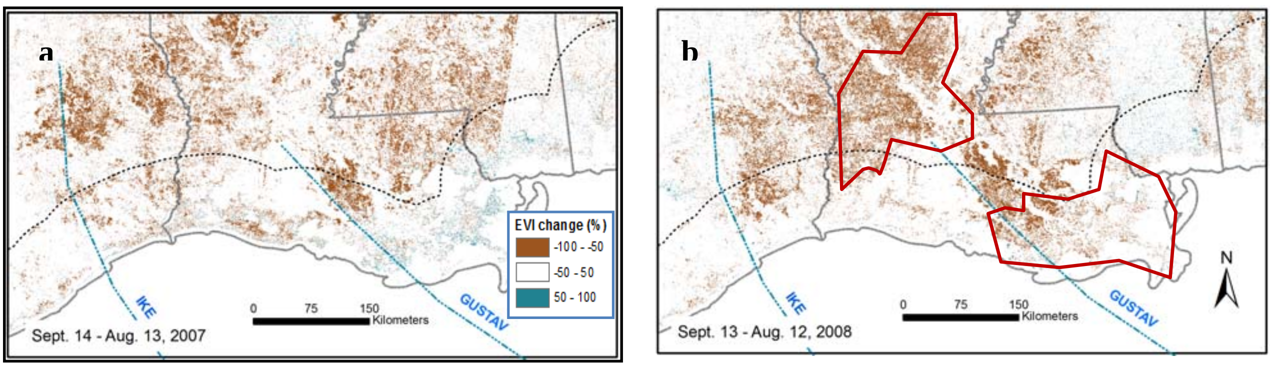


Figure 4. *Cont.*

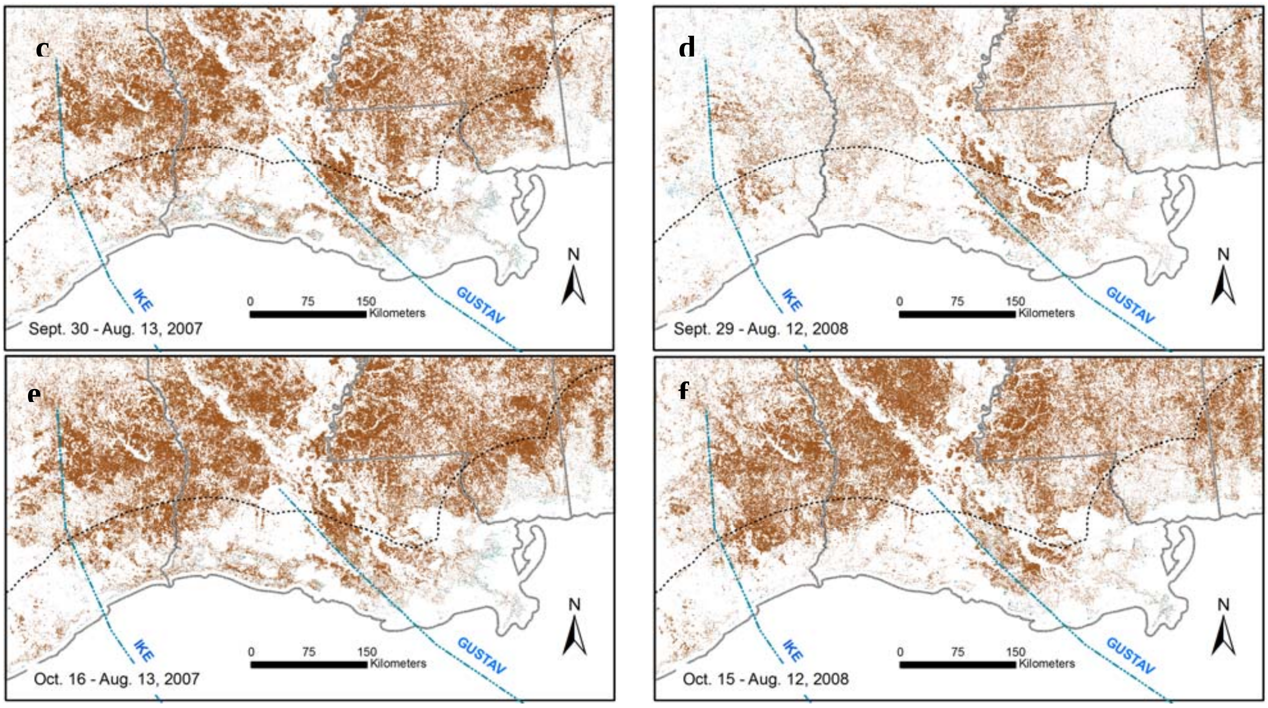


Figure 5. Greater than 45% decrease of the MODIS EVI values between two dates as shown on the maps. The images on the left column, as references, displayed the changes without hurricane disturbance. The maps on the right column represented the changes after Hurricane Lili disturbance.

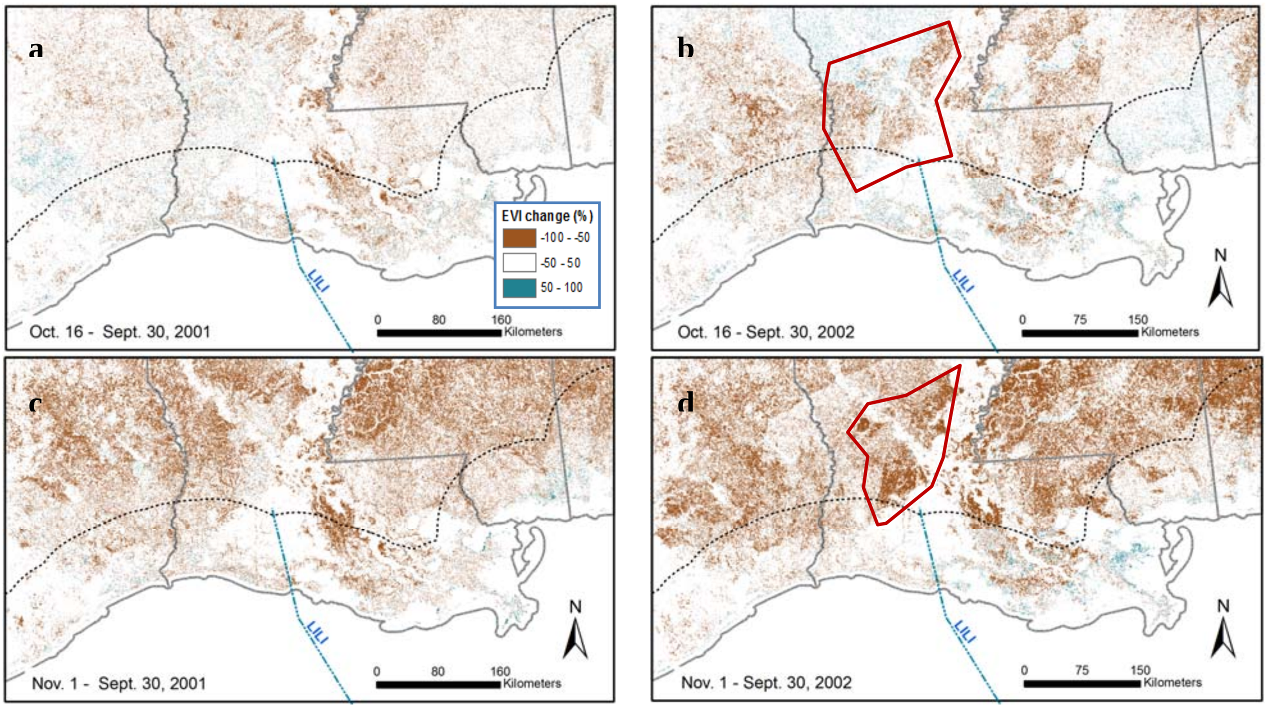
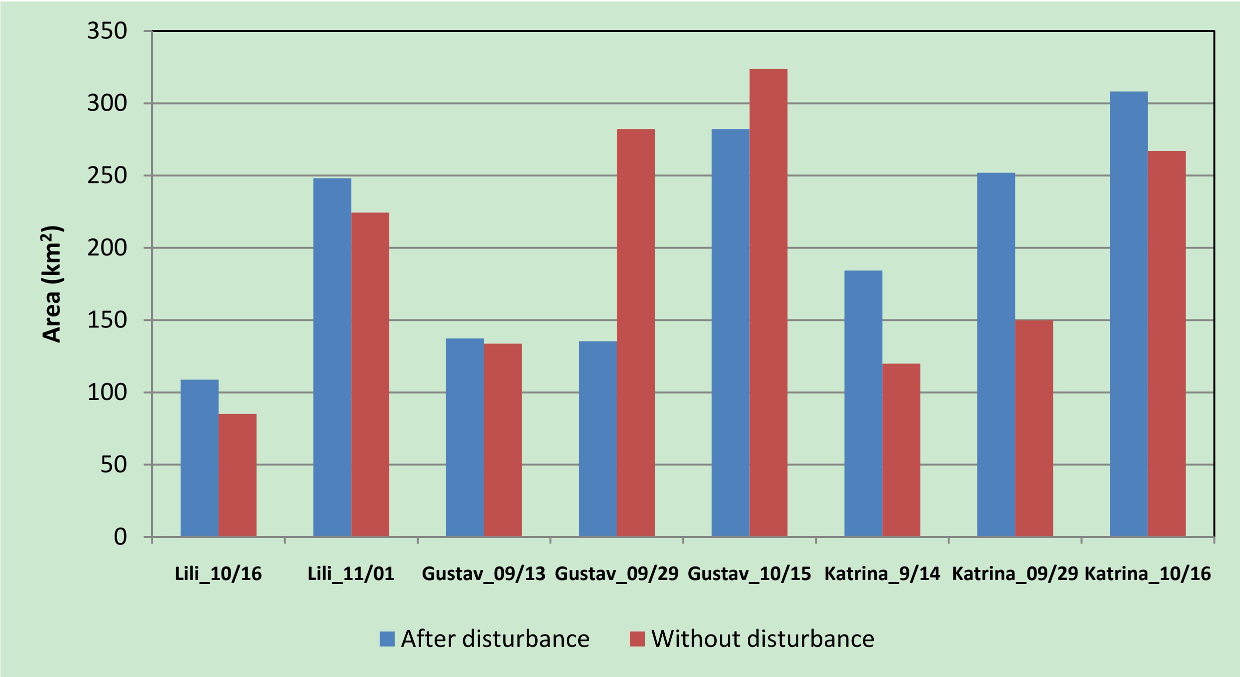


Figure 6. Area of vegetation with greater than 45% decrease of the EVI values from pre- to post-hurricane events in the entire region.

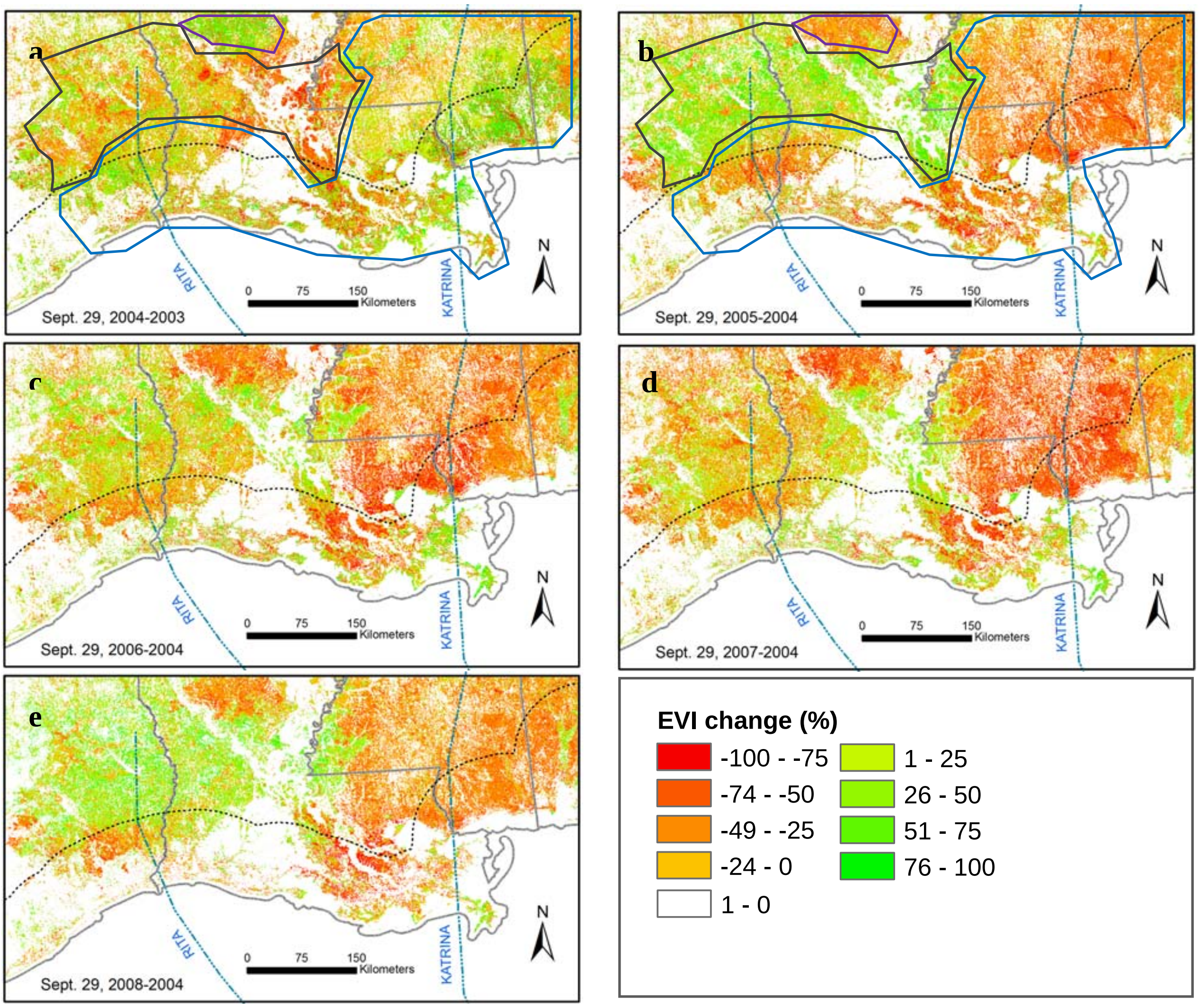


3.2. Disturbance Detection by EVI Changes between Years

3.2.1. Hurricanes Katrina and Rita

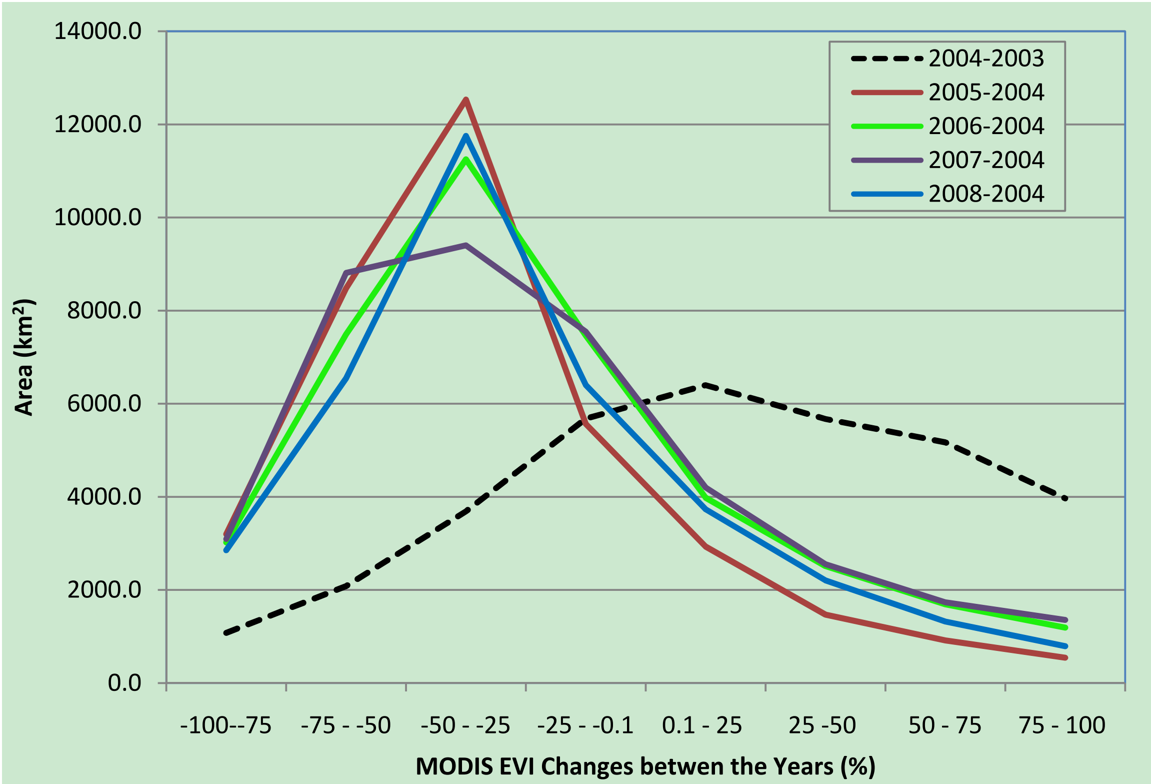
In Figure 7 the temporal changes of the EVI values between 2008–2005 and 2004 were compared to the EVI changes between 2004 and 2003 for the entire region. The spatial patterns were visually grouped into three polygons: pink, black and blue polygons (Figure 7b). For the small pink polygon area in the upper-middle of the region, the EVI values presented a positive change from 2003 to 2004 (Figure 7a). In contrast, the EVI changes in the pink area, between 2005–2008 and 2004 (Figures 7b–7e), displayed negative trends, which implied a disturbance occurrence. However, the pink area was far away from the tracks of Hurricanes Katrina and Rita and it is uncertain if the disturbance was caused by the strong hurricane winds. For the black polygon area, the EVI values after one month of Katrina and five days of Rita's landfall showed an increasing trend as compared to the vegetation conditions in 2004 (Figure 7b). The same trend was also found on the change image between 2008 and 2004 (Figure 7e), when Hurricanes Gustav and Ike struck the coastal area. In contrast, for the same area, the EVI difference between 2006–2007 and 2004 (Figures 7c,d) were very similar with the trend during 2004 and 2003 (Figure 7a), implying the area was less likely disturbed by the hurricanes. However, the increasing EVI values right after the hurricane disturbance (Figures 7b,e) indicated an increase in biomass, leaf area, or coverage in this area. This may have been caused by a fast growth of the forests and understory vegetation triggered by strong precipitation from the storms. The blue polygon area on 2005 change imagery (Figure 7b) represented a very likely disturbance by Katrina and Rita to vegetation. A further intensification in red color in some areas of the blue polygon in 2006 and 2007 (Figures 7c,d) in comparison to 2005 change imagery suggest that it could have been caused by continuous dieback and mortality of the disturbed vegetation and salvage harvest. Meantime, this also implied a severe damage of the hurricane to vegetation. In addition, the color changes from redder to brown since 2005 in some areas in the blue polygon, particularly in the coastal zone, indicated a recovery of the vegetation from the hurricane disturbance.

Figure 7. (a) Percentage changes of MODIS EVI products between 2004–2003, and (b–e) changes during 2005-2008 as compared to 2004. The changes presented in (a) were used as a reference to identify Hurricanes Katrina and Rita disturbance on images b to e.



In the coastal zone within 100 km of the coastal line, the vegetation area variations by the categories of index value changes also showed a strong disturbance due to Katrina and Rita to coastal forests and wetlands and a recovery of the vegetation from the disturbance (Figure 8). Compared to the reference during 2003–2004, the area with negative EVI changes were apparently higher, while the areas with positive changes were lower. Specifically, the areas for the EVI changes greater than 0.1% showed a clear recovery trend. During 2004–2005, the areas in each EVI change categories (>0.1%) was the lowest, then as the wetlands were progressively recovering, the area increased gradually during 2006–2004 to the highest during 2007–2004. But owing to Hurricanes Gustav and Ike disturbance, the area decreased slightly as compared to between 2006 and 2004, and between 2007 and 2004. Yet it was still higher than the area between 2005 and 2004, which meant a lighter damage of Hurricanes Gustav and Ike than Katrina and Rita on the coastal vegetation.

Figure 8. Area of vegetation by category of MODIS EVI changes between the years.



3.2.2. Hurricanes Gustav and Ike

The MODIS EVI changes between September 13, 2007 and 2008 indicated a disturbance pattern to vegetation due to Hurricanes Gustav and Ike as compared to the EVI changes between September 13, 2006 and 2007 in the region within the blue polygon (Figures 9a,b). From September 13 through November 16 (Figure 9h), more green and brown color were displayed in the polygon area, indicating a recovery of the marsh grass, upland forests, and savannas with time. However, a stronger EVI change was observed on September 29 (Figure 9d) than on September 13 (Figure 9b) and the reference image (Figure 9c). In contrast, the image on October 16 and November 16 (Figures 9 f,h) did show a recovery, and during the same time, some vegetation dieback. The vegetation areas in the coastal zone by the categories of the index value changes also confirmed a recovery trend of the vegetation (except for the image on September 29) (Figure 10). The vegetation area with the EVI changes greater than 25% on September 13 was the lowest and experienced the highest rate of decline as compared to the normal conditions. On October 16 and November 17, the areas increased and were greater than the area on September 13. In addition, the area on October 16 was greater than on November 17. These area changes indicated a dynamic change of the coastal vegetation coverage, from a marsh recovery between September 13 and October 16 to a vegetation dieback from October 16 to November 17.

Figure 9. (a, c, e, and g) Percentage changes of MODIS EVI values in the years without hurricane disturbance. (b, d, f, and h) Changes in the EVI value after Gustav and Ike made their landfalls on September 1 and 13, 2009. The map legend is the same as Figure 7.

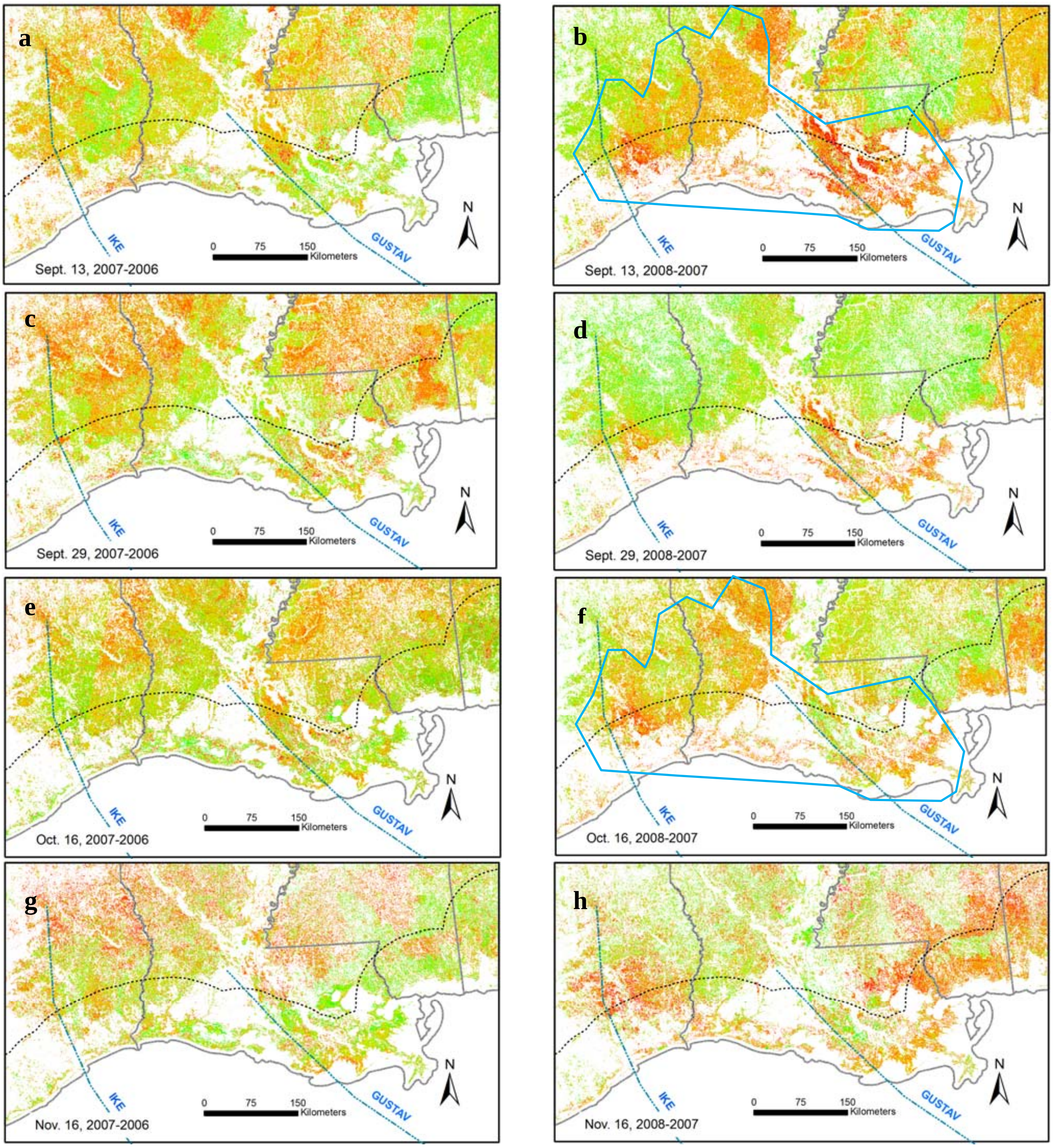
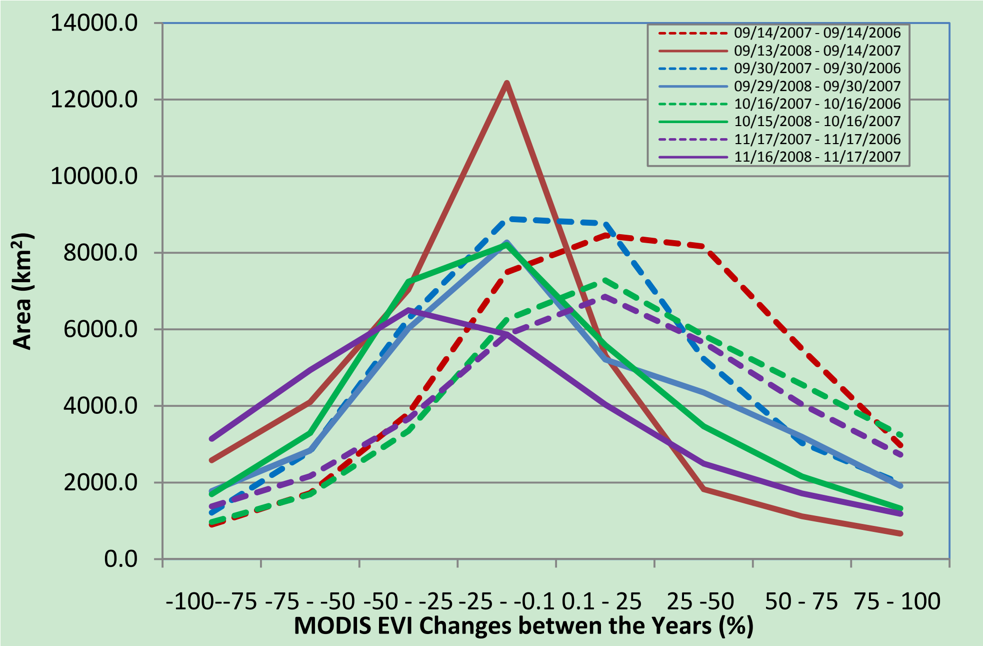


Figure 10. Area of vegetation in the coastal zone by category of MODIS EVI changes between the dates.



3.2.3. Lili

Yearly change of the EVI images revealed that following Hurricane Lili's landfall, vegetation in middle-upper Louisiana and Mississippi displayed an increase in EVI values (Figure 11b) and was in contrast to the declining trend of EVI in the years without hurricane disturbance (Figure 11a). The images on October 31 also displayed a very similar pattern between the reference (Figure 11c) and the image showing the hurricane disturbance (Figure 11d). The vegetation area by categories of the EVI value changes also revealed that the areas with the EVI change less than −25% after the hurricane disturbance were less than the areas in the reference years (Figure 12).

Figure 11. (a and c) Percentage changes of MODIS EVI values in the years without hurricane disturbance. (b and d) Changes in the EVI value after Hurricane Lili made landfall on October 3, 2002. The map legend is the same as Figure 7.

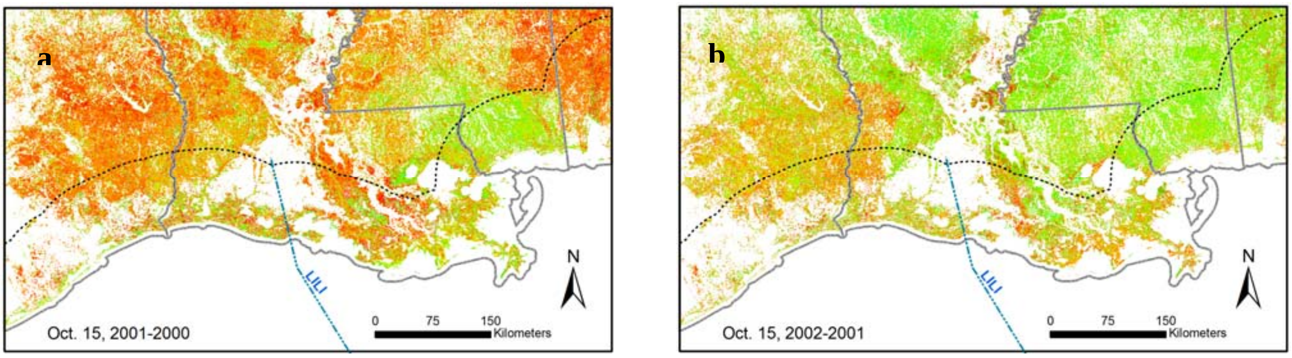
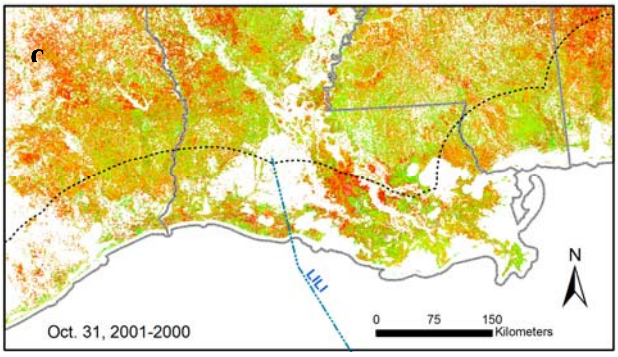


Figure 11. *Cont.*



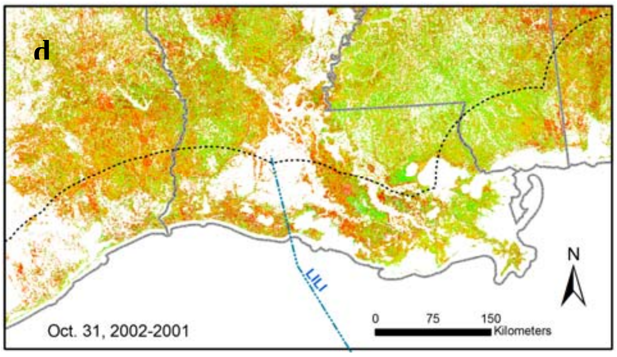
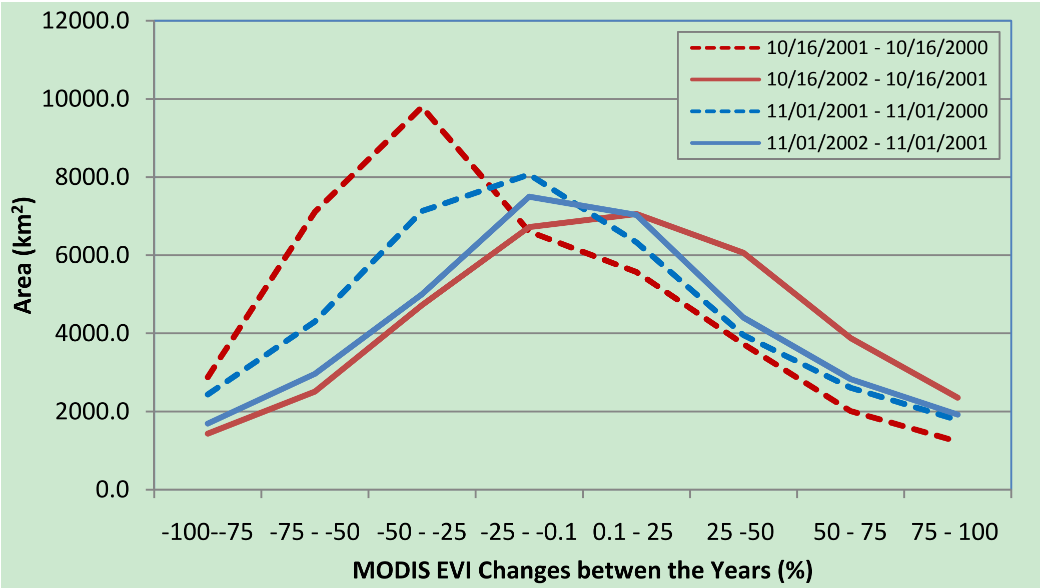


Figure 12. Area of vegetation in the coastal zone by category of MODIS EVI changes between the dates.



4. Discussion and Conclusions

This study examined the use of time series, standardized MODIS vegetation index product to identify vegetation disturbance due to five hurricanes in the US Gulf coast states and to monitor the vegetation recovery over years from the impacts. Our results showed that detection of hurricane damage and vegetation recovery varied by hurricane events and dates of the EVI imagery. For Hurricanes Gustav and Ike, among the eight change images within months or between years (Figures 4 and 9), only two images exhibited likely disturbance patterns as compared to the corresponding reference change images. For Hurricane Lili, the two change images within months (Figure 5) revealed possible damage patterns, but the other two images between the years (Figure 11) did not display any disturbance patterns. Even the vegetation area changes by the EVI change category demonstrated results opposite to our hypothesis that a noticeable negative change of the vegetation index values would have occurred after a hurricane disturbance (Figure 12). As compared to limited or poor damage identification due to Hurricanes Gustav, Ike and Lili, clear disturbance patterns were detected and presented on all images within months or between years for Hurricanes Katrina and Rita (Figures 3 and 7). Particularly, the disturbance pattern by Katrina is more or less comparable to the results by Wang and Xu [14], Nielsen [18], and Wang and Qu [29].

The more detectable disturbance by Hurricanes Katrina and Rita than Gustav, Ike, and Lili with the EVI product could be that the damage of Katrina and Rita to vegetation, particularly upland forests, was more severe than the other three hurricanes, implying that the lighter damage was not detectable by the EVI product or the image differencing algorithm. Lighter damage by Lili, Gustav, and Ike were reported from various resources. For instance, Hurricane Lili only minimally damaged the willows and other vegetation in the Atchafalya Basin, and overall less than five percent of the trees exhibited snaps and blow down [30]. Satellite Landsat imagery exhibited a loss of wetlands and barrier islands off the Louisiana coast and southwest of New Orleans from Hurricane Gustav-related flooding [26]. Hurricane Ike's damage to forests was evident throughout much of East Texas with a total of 191,416 hectares of damaged and affected area and nearly 4 percent of the total East Texas growing stock [31].

Although the likely vegetation patterns disturbed by Hurricanes Katrina and Rita were clearly sketched on the EVI change images as compared to the reference images and the study by Wang and Xu [14] (Figure 3), over the entire image the patterns of the EVI changes with greater than 45% decrease varied over the selected dates. This draws a question about which date of the post-hurricane image is the most appropriate to assess the disturbance. In addition, how does one assess the EVI decline in the presence of natural variability of the vegetation and of the hurricane disturbance? For instance, we cannot sketch a disturbance by Katrina in Figure 3f because the pattern of the image was similar to the EVI changes without the hurricane disturbance (Figure 3e). Compared to the images on the three dates, the image on September 30 appears suitable for identification of Katrina and Rita's disturbance since a maximum and reasonable contrast of the patterns between both images were presented. In addition, the difference of the images on the same day, September 30, but between years (Figure 7b) demonstrated a better result on identification of the disturbance pattern. Therefore, we conclude that the EVI products one month after the disturbance and the image difference between one year just before the hurricane and the year with the hurricane damage would be optimal in representing the vegetation modification by hurricanes. The change image derived by this approach could be applied for a further more accurate assessment of the disturbance, along with the assistance of ground truth or reference data.

This study demonstrated the utility of MODIS EVI product for long-term monitoring of vegetation dynamics after hurricane disturbance. For example, in the case of Katrina and Rita, MODIS EVI products on the same day over a six year period were successful in detecting recovery of vegetation disturbed by the hurricanes (Figure 7). The product can detect not only damage from the disturbance but it may also show vegetation not disturbed by the hurricanes. For instance, the EVI value increase in area labeled as black polygon in Figures 7b,e could be because of fast growth of the vegetation, particularly upland forests from heavy precipitation associated with Hurricanes Katrina, Rita, and Ike. Overall, the successful detection of hurricane disturbance from the MODIS products could vary by many factors including hurricane intensity, site conditions, vegetation vulnerability, quality and availability of the MODIS products. Based on the findings of this study, we think a standardized algorithm for detecting hurricane disturbance with MODIS products could be developed with the aid of extensive ground truth and analysis of the products with other statistical methods or modeling techniques.

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