ABSTRACT

Title of Document: THE EFFECT OF HURRICANE SANDY ON NEW JERSEY ATLANTIC COASTAL MARSHES EVALUATED WITH SATELLITE IMAGERY

Diana Marie Roman, Master of Science, August 2015

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Hurricane Sandy, one of several large extratropical hurricanes to impact New Jersey since 1900, produced some of the most extensive coastal destruction within the last fifty years. Though the damage to barrier islands from Sandy was well-documented, the effect of Sandy on the New Jersey coastal marshes has not. The objective of this analysis, based on twenty-three Landsat Thematic Mapper (TM) data sets collected between 1984 and 2011 and Landsat 8 Operational Land Imager (OLI) images collected between 2013 and 2014 was to determine the effect of Hurricane Sandy on the New Jersey Atlantic coastal marshes. Image processing was performed using ENVI image analysis software with the NDX model (Rogers and Kearney, 2004). Results support the conclusion that the marshes were stable between 1984 and 2006, but had decreased in vegetation density coverage since 2007. Hurricane Sandy caused the greatest damage to low-lying marshes located close to where landfall occurred.

THE EFFECT OF HURRICANE SANDY ON NEW JERSEY ATLANTIC COASTAL MARSHES EVALUATED WITH SATELLITE IMAGERY

by

Diana Marie Roman

Thesis submitted to the Faculty of the Graduate School of the
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Forward

Hurricane storm impacts on coastal salt marshes have increased over time. The goal of this study is to find the effects of Hurricane Sandy on the Atlantic coastal marshes within the marsh area where Hurricane Sandy made landfall and hopefully start a log of hurricane impacts specific to the New Jersey coastal salt marshes.

Dedication

I would like to dedicate this thesis to my family: Tony Roman, Sharon Roman and Julie Roman. Without their love and encouragement I would not have pushed myself towards higher education and achieving my Master's Degree. My friends from St. Mary's College of Maryland Allyson Devers and Karen Espinoza, University of Maryland Ruth Shirley and Alex Duplessie, and multiple rugby teams including the St. Mary's Seahawks and Maryland Stingers as well as my research lab for all of their support and assistance throughout my entire Masters experience. This study included logging many hours in lab as well as in the field. The stress and sleepless nights of this experience would have taken over if it were not for my small, but powerful support system.

Acknowledgements

I want to acknowledge the Shirley family for their great seal of moral support and for giving me affordable housing so that I was able to focus on my research and not on finances. I want to thank Drs. E. Ramsey III, A. Rangoonwala, A. Riter and M. Yu for their reassurance, teaching and aid both in the field and during the thesis writing process. I owe special thanks to Dr. Michael Kennish of Rutgers University, who generously shared the results of his current research on the Tuckerton Peninsula.

I am extremely grateful to the members of my thesis committee, Dr. Andrew Elmore and Dr. Andrew Baldwin, for the many hours of work and constructive information that they provided.

I want to personally thank Dr. Michael S. Kearney for all of his patience, encouragement and assistance during my entire Masters research and thesis experience and his financial support in the form of a Graduate Research Assistantship.

Lastly, I want to thank the United States Geological Survey for funding this research project.

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Chapter 1: Introduction

Marshes and wetlands serve many important functions such as providing various habitats, buffer stormy seas along coastlines, slow shoreline erosion and absorb excess nutrients from stream and runoff before their waters reach the estuaries and oceans (Kennish, 2001). These marsh functions have become more important as the human population and anthropogenic coastal alterations increase over time.

Coastal marshes are among the most threatened of ecosystems, facing threats from rising sea levels, anthropogenic activities, and extreme meteorological events, such as major storms, droughts, intense winds. Though the effects of an acceleration in sea level rise have received considerable attention with respect to the survival of coastal marshes (Morris et al., 2002), it is become increasingly clear that the impacts of the other two factors, human activities and storms, can enhance the vulnerability of coastal marshes to sea level change. However, it is not always certain what long term affects these factors, either singly or combined, can have on the resilience of coastal marshes with respect to sea level changes.

Hurricane Sandy made landfall along the southern New Jersey shoreline on October 29, 2012, just north of Brigantine, New Jersey, causing massive devastation along the coast. As one of the largest and most powerful extratropical cyclones in recent memory (Table 1), Hurricane Sandy was accompanied by a large storm surge and damaging waves that caused maximum inundation about 1.5 to 1.8 meters (Blake et al, 2013) (Figure 1 and 2).

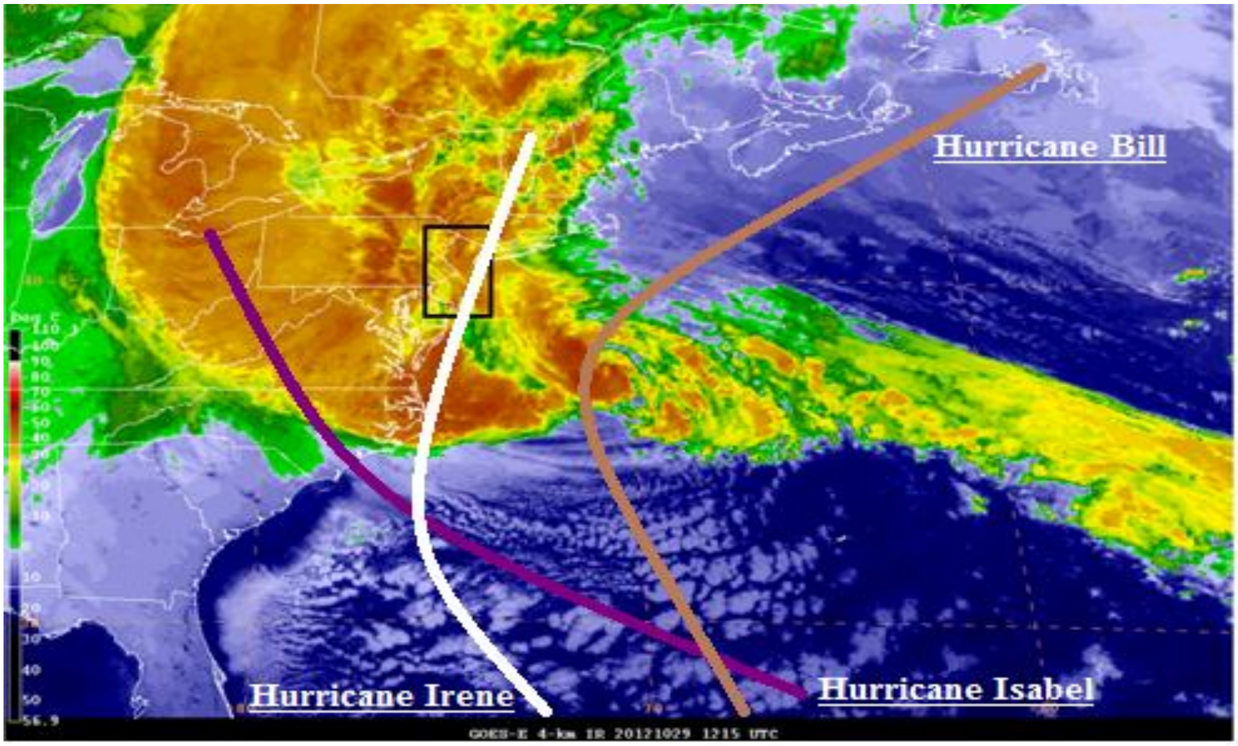

Figure 1. GOES-E infrared satellite image of Sandy at 1215 UTC 29 October 2012, near its secondary peak intensity (Blake et al, 2013). The black box area surrounds the state of New Jersey. The dark red color indicates the intensity of Hurricane Sandy over the state. Each color line tracks a specific Pre-Hurricane Sandy storm including Hurricane Isabel (purple), Hurricane Bill (brown) and Hurricane Irene (white).

The objective of this study was to determine the effect Hurricane Sandy had on the New Jersey coastal marshes near where the hurricane made landfall (Figure 3). To fulfill the objective of this study I examined Landsat Thematic Mapper (TM) (1984-2011) and Operational Land Imager (OLI) (2013-2014) data sets to examine the effect of Sandy in a historical context between 1984 and 2014 in Landsat Path 14 and Rows 32 and 33. Because the Landsat TM sensor failed in November 2011, two SPOT 5 data sets from October 13, 2012 and December 30, 2012 were examined to detect changes in marsh area immediately before and after Hurricane Sandy. The 10 m spatial resolution of the SPOT 5 data sets can detect finer-scaled changes that the 30 m spatial resolution of Landsat data sets cannot resolve.

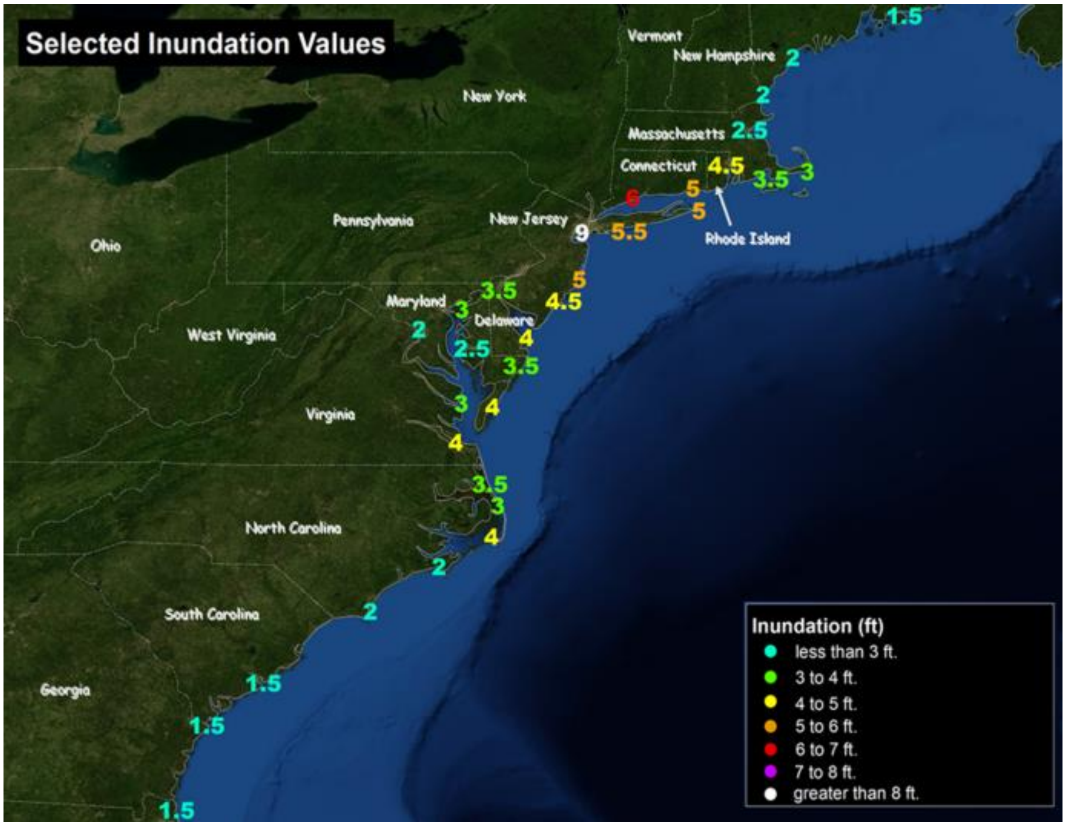

Figure 2. Map of mid-and north-Atlantic coast showing estimated inundation from Hurricane Sandy. Inundation, in feet above ground level and rounded to the nearest half-foot, is estimated from USGS high-water marks and NOS tide gauges (Figure 24 from Blake et al. 2013).

Spectral unmixing of Landsat Normalized Difference Vegetation, Water, and Soil, Indices (NDVI, NDWI, NDSI) with an accurate data set-derived vegetation, water, and soil endmembers, has been shown to accurately estimate the percentage of marsh vegetation cover space (Kearney et al. 2011, Kearney et al. 2011). This technique has been applied in Louisiana, Maryland, Delaware, and other mid-Atlantic marshes to evaluate changes in marsh vegetation condition over time and space (Rogers and Kearney, 2004; Kearney et al. 2011a, Kearney et al. 2011b). Clip plot data visually estimated to be representative of marsh vegetation density and cover. The clip plots provide a second means of evaluating the cover of the marsh vegetation.

Table 1. Hurricanes with strong storm surges that affected the New Jersey coastline since 1900.

Date	Name	Storm Surge
9/19/1936	Unknown "Category 2"	Strong waves flood Long Beach Island and cause severe beach erosion. 61 m of sand is lost near Barnegat Lighthouse.
9/21/1938	New England Hurricane	Strong winds up to 100 mph and powerful storm surge.
09/13/1944-09/14/1944	Great Atlantic Hurricane	Caused severe flooding, a storm surge up to 2.9 m and intense waves up to 12.2 m. Strong winds gusting to 125 mph and was a category 2 hurricane.
9/12/1960	Hurricane Donna	Category 2 hurricane caused significant damage along the coastline. Hurricane caused wind gusts up to 105 mph, heavy rainfall and a storm surge of 1.8 m.
8/10/1976	Hurricane Belle	Caused winds of 65 mph and gusts of 90 mph, along with a maximum total rainfall of 9.98 cm. The hurricane caused a storm surge of 2.7 m.
9/27/1985	Hurricane Gloria	Category 2 hurricane caused a storm surge of 1.4 m and wind gusts of 80 mph. Light rainfall along the shoreline, but further inland.
9/1/1989	Hurricane Gabrielle	Produced strong waves up to 4.9 m in height.
10/31/1991	"Perfect Storm"	Waves up to 9.1 m, significant flooding, beach erosion.
9/19/2003	Hurricane Isabel	Strong storm surge of up to 3.2 m. Persistent strong waves severely erode coastline.
8/22/2009	Hurricane Bill	Strong waves as high as 4.6 m. Stormed passed as Category 1 hurricane.
8/27/2011-8/28/2011	Hurricane Irene	Major flooding, downed trees, caused coastal communities to evacuate. Waves up to 9.9 m.

Hurricanes have the potential to cause positive and negative effects on coastal marshes. The processes, by which positive and negative occur, can be tentatively identified by the locations where land gain (positive effect) and land loss (negative effect) occur. The processes of storm surge, salt inundation, flooding due to heavy precipitation, and wind and wave damage can lead to the formation and enlargement of interior ponds, culm damage, shore erosion and loss of surface accretion which have been documented in other hurricane studies (Morton and Barras, 2011, Turner et al., 2006; Barras, 2007; McKee and Cheery, 2009; Reed et al., 2009).

Chapter 2: Description of field area

The New Jersey Atlantic coastal marshes extend from Sandy Hook, NJ south to Cape May, NJ into the Delaware Bay. This research project concentrates on the area where Hurricane Sandy's effects were most concentrated near Brigantine, NJ (Figure 3).

The New Jersey coastal marshes are developed over Holocene and older New Jersey coastal plain sediments. The sediments consist of an eastward-thickening wedge of unconsolidated river/ deltaic and marine sediments, mainly composed of sand, silts, and clays (Owens and Sohl, 1969). The soil beneath the New Jersey coastal salt marshes is very fine-grain clay mixed with carried to the estuary and coastline from freshwater rivers (Nordstrom, 1977).

The lagoon marshes overlie unconsolidated, and easily erodible, riverine and marine sediments. Barrier islands, composed predominantly of unconsolidated sands, line the New Jersey coastline. Tidal inlets occur about every 10 miles along the barrier islands.

A daily semi-diurnal tide occurs along the New Jersey coastline from Cape May to Sandy Hook and beyond. The average tidal cycle water level change in the Atlantic City area is 1.2 to 1.5 meters (m) (NOAA).

The New Jersey coastal marshes are populated by halophytes. The low marsh, flooded once daily by the tide, is dominated up to the mean high water level by the tall form of *Spartina alterniflora* (saltwater cordgrass) (Tiner, 1985). Above the low marsh is the high marsh which is less often flooded by the tides. A short form of *Spartina alterniflora* dominates in the high marsh. Plant diversity increases in the high marsh with the reduction in tidal flooding and salinity (Tiner, 1985). Several species become abundant including *Spartina patens* (salt hay grass), *Distichlis spicata (spike grass), Juncus gerardii* (black grass), *Panicum virgatum* (switch-grass), *Iva frutescens* (marsh elder), *Salicornia virginica* (pickle weed) and *Phragmites australis* (invasive common reed) as well as a variety of other common mid-Atlantic salt marsh plants (Tiner, 1985). The brackish marshes in the mesohaline areas of the New Jersey estuaries have a large range of salinity (5 to 18 ppt) compared to salt marshes which are classified as 18-30 to >30 (Cowardin, 1978) and mark a transition between saline marsh vegetation species and freshwater species (Tiner, 1985).

Chapter 3: Methodology

The primary data for this research consisted of satellite data and a biomass study. The satellite data consisted of imagery from Landsat TM 5, Landsat OLI 8 and SPOT 5. The finer scale spatial resolution (10 m) SPOT 5 data was included primarily to fill the gap in satellite data caused by the failure of Landsat TM sensor in November of 2011 and the launch of Landsat OLI in February of 2013. The biomass study consisted of specific clip plot locations within the study area. The specific clip plot locations were representative of the average marsh vegetation cover based on visual observations in the field. In each case I will describe the data sets used and the processing protocol.

Satellite Data

Landsat data sets

Twenty-three Landsat Surface Reflectance Climate Data Record (LSRCD) Landsat TM 5 and OLI 8 data sets (http://landsat.usgs.gov/ documents/ledaps_add.pdf) were downloaded from USGS Earth Explorer website (http://earthexplorer.usgs.gov/) to use in this study (Table 2). These data sets are Landsat Surface Reflectance Climate Data Records (CDRs) and are processed by NASA personnel using the Landsat Ecosystem Disturbance Adaptive Processing

System (LEDAPS) software, which applies Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric correction routines to Landsat Level-1 scenes (Masek et al, 2006). The LEDAPS atmospheric correction is extremely accurate because the MODIS satellite has 36 spectral bands, some of which are specifically designed to determine atmospheric conditions. This allows for an extremely accurate atmospheric correction of the Landsat data.

Table 2. Mean Lower Low Water level (MLLW) at the acquisition time (GMT) for each data set. *

Image Date	Acquisition time (GMT)	Atlantic City, NJ water level (cm)
1984-0921	1984:265:15:10:36.59244	75.1
1988-0831	1988:244:15:11:17.31844	151
1995-0904	1995:247:14:42:57.66950	30.3
*1996-0720	1996:202:14:55:10.67275	108.6
1996-0805	1996:218:14:56:01.43881	100
1998-0912	1998:255:15:19:13.93781	123.9
2000-0917	2000:261:15:18:43.94825	128
2003-0825	2003:237:15:17:39.36731	8.3
2005-0814	2005:226:15:28:31.81306	67
*2006-0801	2006:213:15:33:45.50350	110.3
2006-0817	2006:229:15:33:56.55525	73.1
*2006-1207	2006:341:15:34:40.01606	123.57
*2007-0617	2007:168:15:34:30.67644	107.4
2007-0804	2007:216:15:33:58.12513	129.7
*2007-0905	2007:248:15:33:12.03400	89.09
2008-0907	2008:251:15:24:56.30313	105.37
*2009-0521	2009:141:15:27:31.89231	-14.11
2009-0825	2009:237:15:29:57.99413	151.7
2010-0828	2010:240:15:29:56.12988	130.18
2011-0831	2011:243:15:28:20.67881	135.18
*2013-0601	2013:152:15:42:34.2811720	60
2013-0719	2013:200:15:42:29.8556510	11.2
2014-0807	2014:219:15:40:09.5640909	32.98

* Multiple data sets were processed for the years 1996, 2006, 2007, 2009 and 2013. Data sets in with asterisks next to the date were not used in the final statistical analysis shown in Figure 6.

The criteria used for selection of Landsat data sets were: 1) dates coinciding with peak or near-peak vegetation growth through based on image appearance on GLOVIS web site and the date of the data collection; 2) a tidal stage near mean low lower water (MLLW); 3) high atmospheric clarity (little haze or cloud cover); 4) dates before and after major storms when possible; and 5) regular intervals between data sets. Rarely were all criteria met, which is typical of most remote sensing studies; however, the data sets chosen for the final study were judged to be acceptable if they met most criteria. There were enough images found to perform this study to only use Landsat data sets with either little to no haze or cloud cover and cloud shadows over the marshes.

Landsat Image Processing

The 23 Landsat images chosen were from Path 14 Row 32 and Row 33 to create the entire New Jersey coastline. Multiple clear images for the years 1996, 2006, 2007, 2009, and 2013 are shown in Table 2. All images were processed find which ones were closest to peak marsh vegetation. These peak vegetation images were then chosen for statistical analyses. Processing of each image was performed using ENVI image analysis software (http://www.exelisvis.com/ProductsServices/ ENVIProducts.aspx). All Landsat images were resized to the same geographic area (Figure 3) and masks were created to eliminate all land cover types other than marshland, marsh creeks, and water bodies within the lagoon marshes. The water mask created from the 2011-0831image allowed for an increase in marsh area.

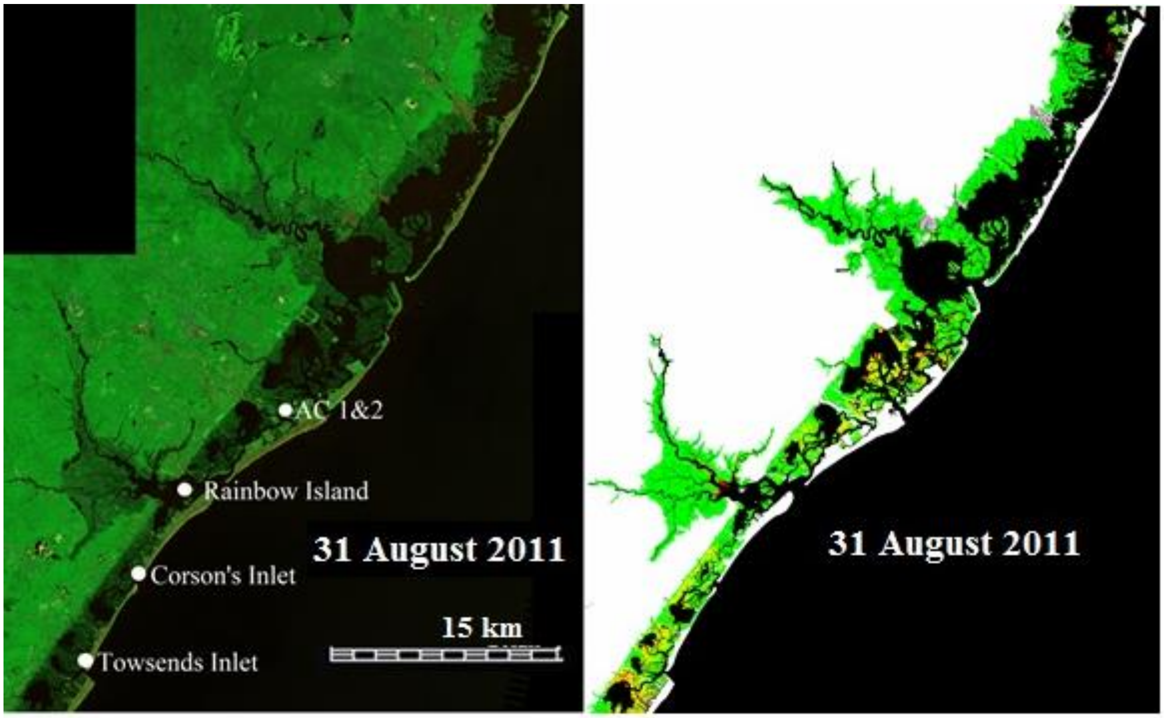

Figure 3. The August 28, 2010 surface reflectance data set on the left shows the biomass collection sites for the biomass validations study. AC indicates the Atlantic City site. The August 31, 2011 marsh surface condition map is shown on the right. Green indicates high density live marsh vegetation (greater than 40%), yellow indicates moderate density live marsh vegetation (20 – 40%), and red indicates low density marsh vegetation (less than 20%). White indicates all land cover types other than marshland, marsh creeks, and water bodies within the coastal marshes. Black indicates water. Scale bar on the August 28, 2010 image is 15 km long.

Spectral unmixing of the Landsat surface reflectance data was used to estimate percent marsh vegetation with the method described by Rogers and Kearney (2004). The standard mixture model is represented as:

$$R_i = \sum_{j=1}^{n} \rho_{ij} \; f_j + e_i$$

where n is the number of bands,
ρ_{ij} is the surface reflectance of land cover type j for band i,
f is the fraction of the pixel covered by land cover j, and
e_i is the error in band i including random noise, instrument and calibration error.

The assumptions for this standard mixture model are as follows: 1) Every marsh pixel is a composite of one to three spectrally pure land cover types (marsh vegetation, marsh substrate, and water), (i.e. Σf_j = 1.0000 and $0 \leq f_j \leq 1.0000$ for all f_js); 2) the signal received at the satellite is the linear, weighted sum of the radiances from each of the three cover types in the pixel; 3) the number of land cover types cannot exceed the number of spectral bands used; so Landsat TM bands 3, 4, and 5 are used to define the spectral characteristics of the pure three land cover types or end members: marsh vegetation, marsh soil, and water) and 4) the percentage of each pixel characterized by vegetation, soil, and water is determined by inverting equation 1and solving for each f_j. Then, I created three spectral indices derived from each image data set for the Landsat 4-5TM bands 3, 4, and 5 using the equations shown below:

1. Normalized Difference Water Index (NDWI): (band 3- band 5)/ (band 3 + band 5);
2. Normalized Difference Vegetation Index (NDVI): (band 4-band 3)/ (band 4 + band 3);
3. Normalized Difference Soil Index (NDSI): (band 5-band 4)/ (band 5 + band4) (Rogers and Kearney, 2004).

The same equations are used for Landsat 8 OLI data sets except the Landsat OLI red, Near Infrared (NIR), and Short Wave Infrared (SWIR) bands are numbered bands 4, 5, and 6.

The NDX model is defined in terms of the principal cover types that characterize most marshes (vegetation, water and soil), but the model mathematically separates items that are brighter in band 5 then band 4 (soil) from those that are brighter in band 3 than band 5 (water) and those whose maximum difference in brightness is between bands 3 and 4 (vegetation). Principal component analysis has been used for similar studies; however, it has been found empirically that spectral unmixing produces more accurate results thought in large part due to the wide scatter of marsh soil/ soil substrate surface reflectance (Figure 3).

Advantages of spectral mixing model based on Normalized Difference Indices are that they reduce the errors produced by application simple models of linear spectral unmixing caused by the highly variable composition and large range of spectral signatures of marsh substrate. Also, the indices produce more accurate linear unmixing results than Principle Component Analysis or linear unmixing results using surface reflectance of land cover endmembers. These advantages lead to Marsh Surface Condition Indices (MSCI) and Marsh Surface Condition Maps. These maps are created by defining ranges of % vegetation, water, and soil based on field observation of Category 1 (greater than 40% marsh vegetation cover), Category 2 (between 40 and 20% vegetation cover), and Category 3 marsh (less than 20% vegetation cover)..

Sources of error include inaccurate atmospheric correction. NDVI is very sensitive to inaccurate atmospheric correction. The sensitivity of NDVI decreases at high vegetation cover percentages due to a plateauing effect. Lastly, inaccurate end member spectral signatures of land cover types; i.e. finding pixels with “pure” soil end member is difficult during peak vegetation months. Best results are obtained with data set-derived spectral end member signatures, and sun glint on water bodies and waters turbid with sediment, can provide poor endmember spectral signatures that produce inaccurate unmixing results.

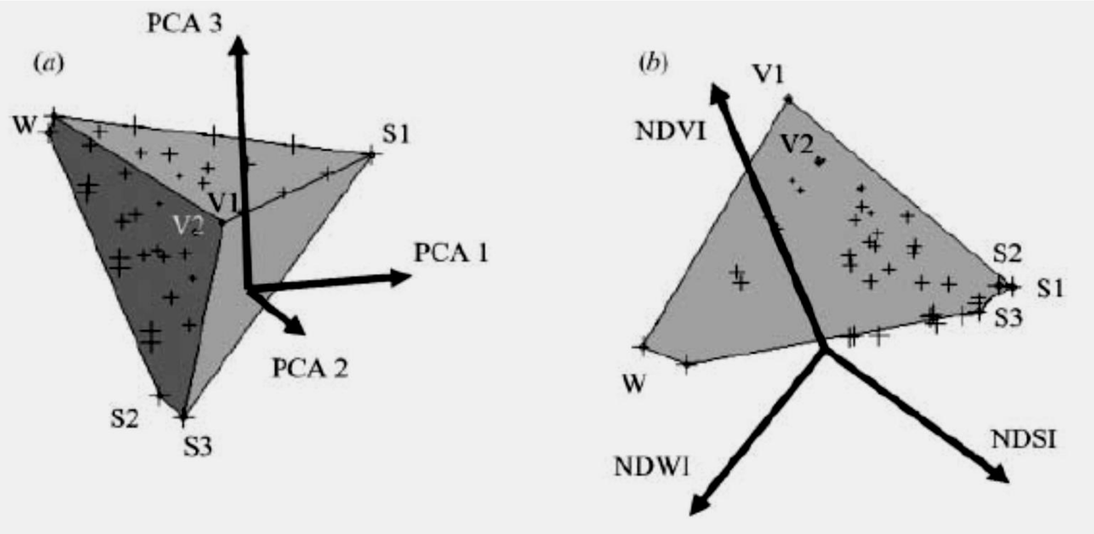

Figure 4. Distribution of pixels in (*a*) principle components and (*b*) NDX data spaces. The soil indices (+) are more scattered in (*a*) principle component analysis, while in (*b*) NDX data spaces the soil indices are more clustered. Therefore, the NDX space produces more accurate results than principle component analysis (Rogers and Kearney, 2004).

SPOT 5

The wave lengths for each of the bands used for spectral unmixing of the Landsat 5TM, Landsat 8 OLI are slightly different (Table 3). Although these differences will affect the results of the spectral unmixing, the resulting differences are thought to be minimal (Table 3).

Table 3. Wavelengths in micrometers of the Red, Near Infrared (NR), and Short Wave Infrared (SWIR)bands of the Landsat TM, Landsat OLI and SPOT 5 sensors. The differences between the wavelengths for Landsat TM 5, Landsat OLI 8 and SPOT 5 satellites are small and will affect the results, but not to a large extent.

	Landsat TM			Landsat OLI			SPOT 5		
Type	Band	Wavelengths (μm)	SR (m^2)	Band	Wavelengths (μm)	SR (m^2)	Band	Wavelengths (μm)	SR (m^2)
Red	3	0.63 - 0.69	30	4	0.64 - 0.67	30	2	0.61 – 0.68	10
NIR	4	0.77 - 0.90	30	5	0.85 - 0.88	30	3	0.78 -0.89	10
SWIR	5	1.55 - 1.75	30	6	1.57 - 1.65	30	4	1.58 – 1.75	10

Validation

Biomass Data

The extensive salt marsh islands along the mainland shoreline and the salt marsh islands in the bay are predominately low and high salt marshes, with *Spartina alterniflora* as the dominant species in the low marshes and *Spartina patens* is the dominant species in the high marshes (Breden, 1989; Tiner, 1985).

During the biomass study, the tide was coming in moving from a low tide at 7:42 GMT with a water level of 0.22 m to high tide at 14:06 GMT with a water level of 1.59 m (NOAA tide gauge 8534720 Atlantic City, NJ).

We harvested biomass from five field sites from Atlantic City, NJ to Towsend Inlet, NJ using one circular clip plot (1 meter in diameter) per sampling area (Figure 3). All vascular plants within each plot were clipped at ground level (within 1 cm of the surface of the marsh mat) and placed in labeled black plastic trash bags for transportation to the lab at University of Maryland College Park. The harvested plant material once returned to the laboratory was sorted into live plant material and dead plant material and species. The main plant species within all the site clip plots was *Spartina alterniflora* (marsh cordgrass) with some *Spartina patens* (marsh hay). The harvested plant material was then oven-dried at 60 degrees Celsius to constant mass. I recorded the species of plant material and live as well as dead biomass weight (g dry weight; Sasser et al., 1994) and compared the weights between collection sites.

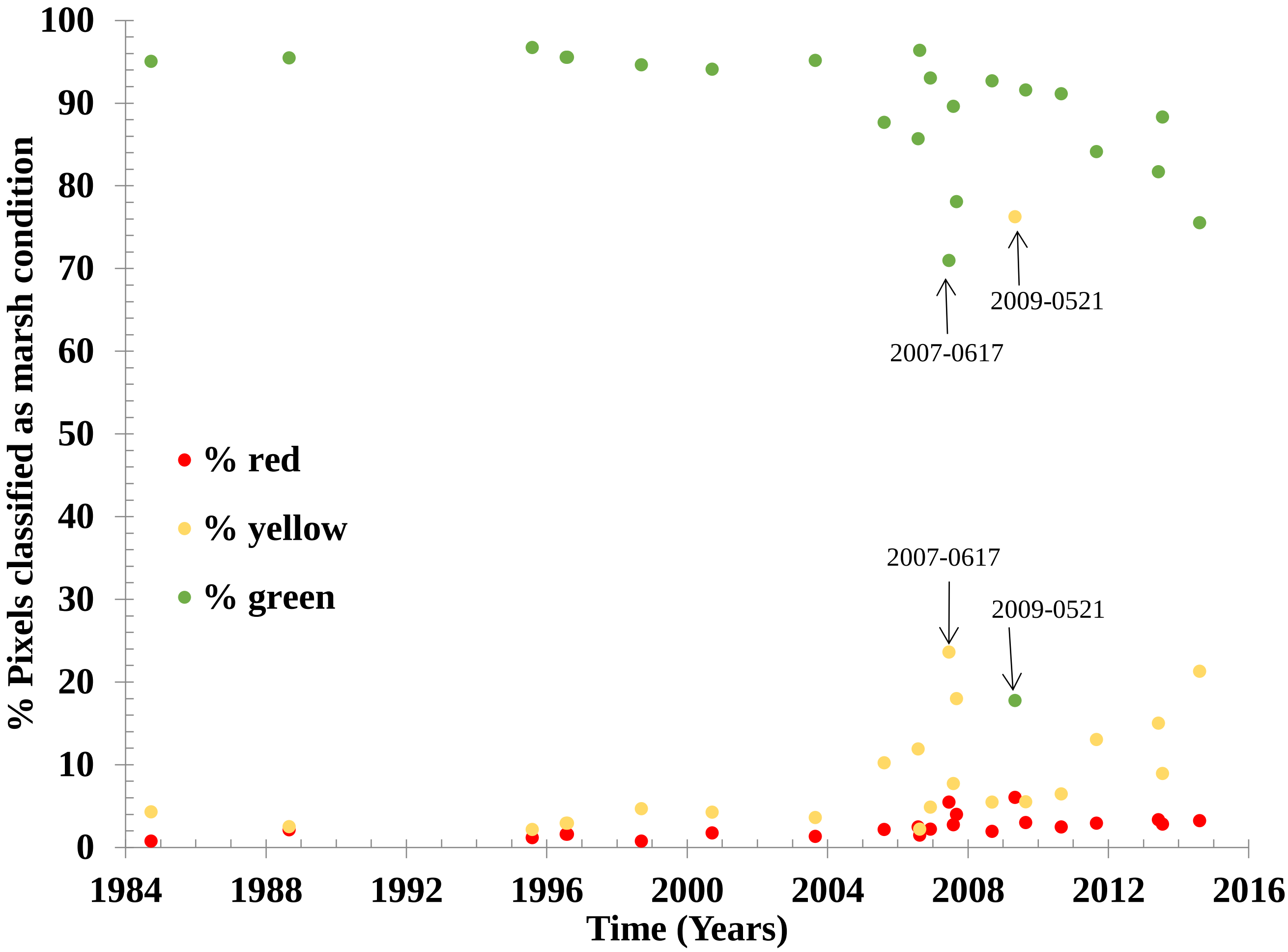

Figure 5. Variation in the percentage of pixels classified as Category 1 (green circles), Category 2 (yellow circles), and Category 3 (red circles) from Landsat TM and OLI data sets from 1984 to 2014. The percentages of pixels are from the entire marsh area of the footprint satellite image. The principle cause of the scatter is due to inter-annual variation through the growing season due to the inclusion of multiple data sets plotted for the years 1996, 2006, 2007, 2009 and 2013. See Figure 10. Note the large decrease in Category 1 marsh for 2008-2009, which reflect the exceptional sea level high stand for the Atlantic Coast, a 1-in-850 year event (Goddard et al., 2015).

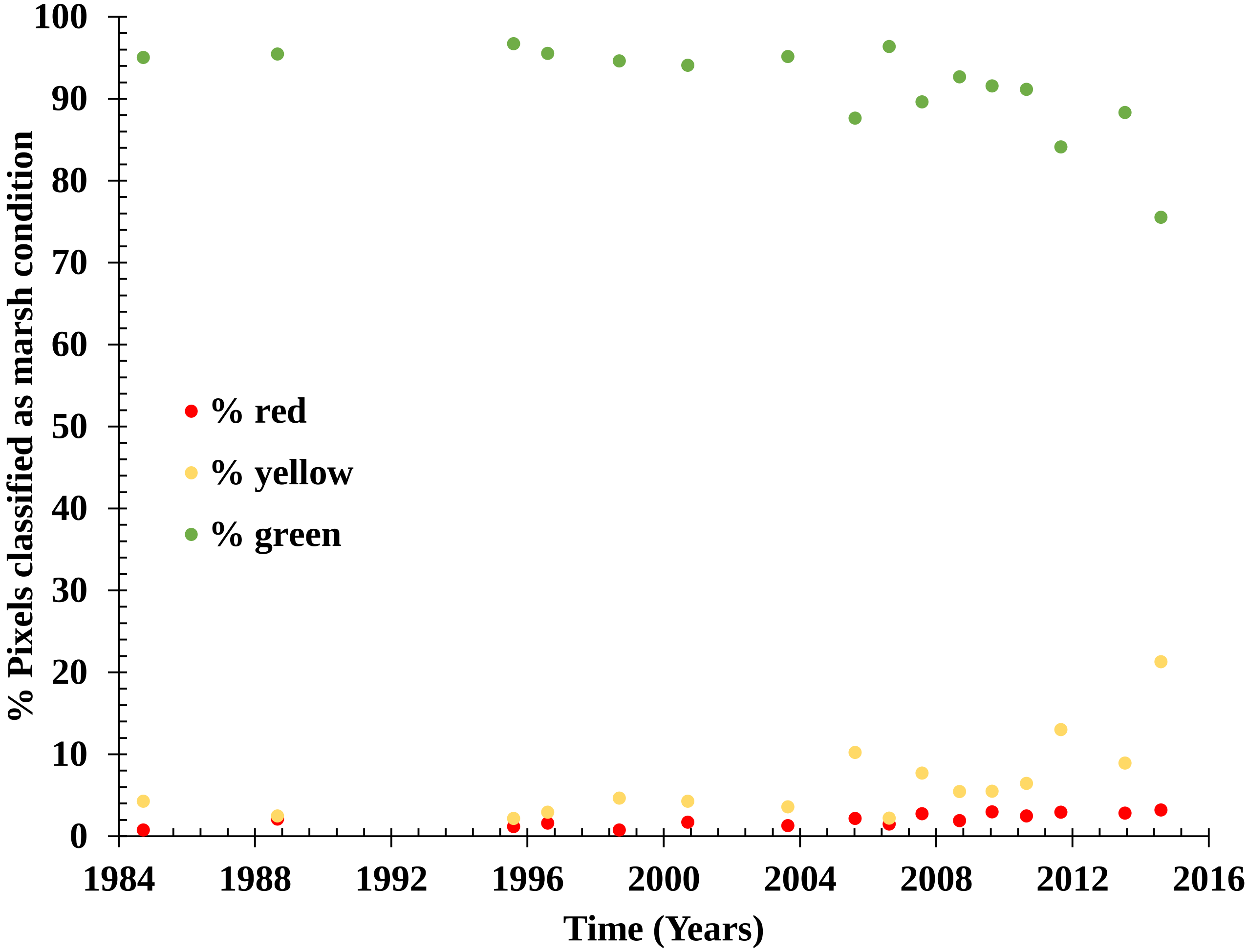

Figure 6. Variation in the percentage of pixels classified as Category 1 (green circles), Category 2 (yellow circles), and Category 3 (red circles) from Landsat TM and OLI data sets from 1984 to 2014. The percentages of pixels are from the entire marsh area of the footprint satellite image. Only the data set with the highest calculated % Category 1 vegetation is plotted for each of the years. Removing the intra-annual (seasonal) variation produces results that suggest minor inter-annual variation between 1984 and 2010, although there appears to be a general decrease in the percentage of Category 1 marsh pixels after 2006. See Figure 11.

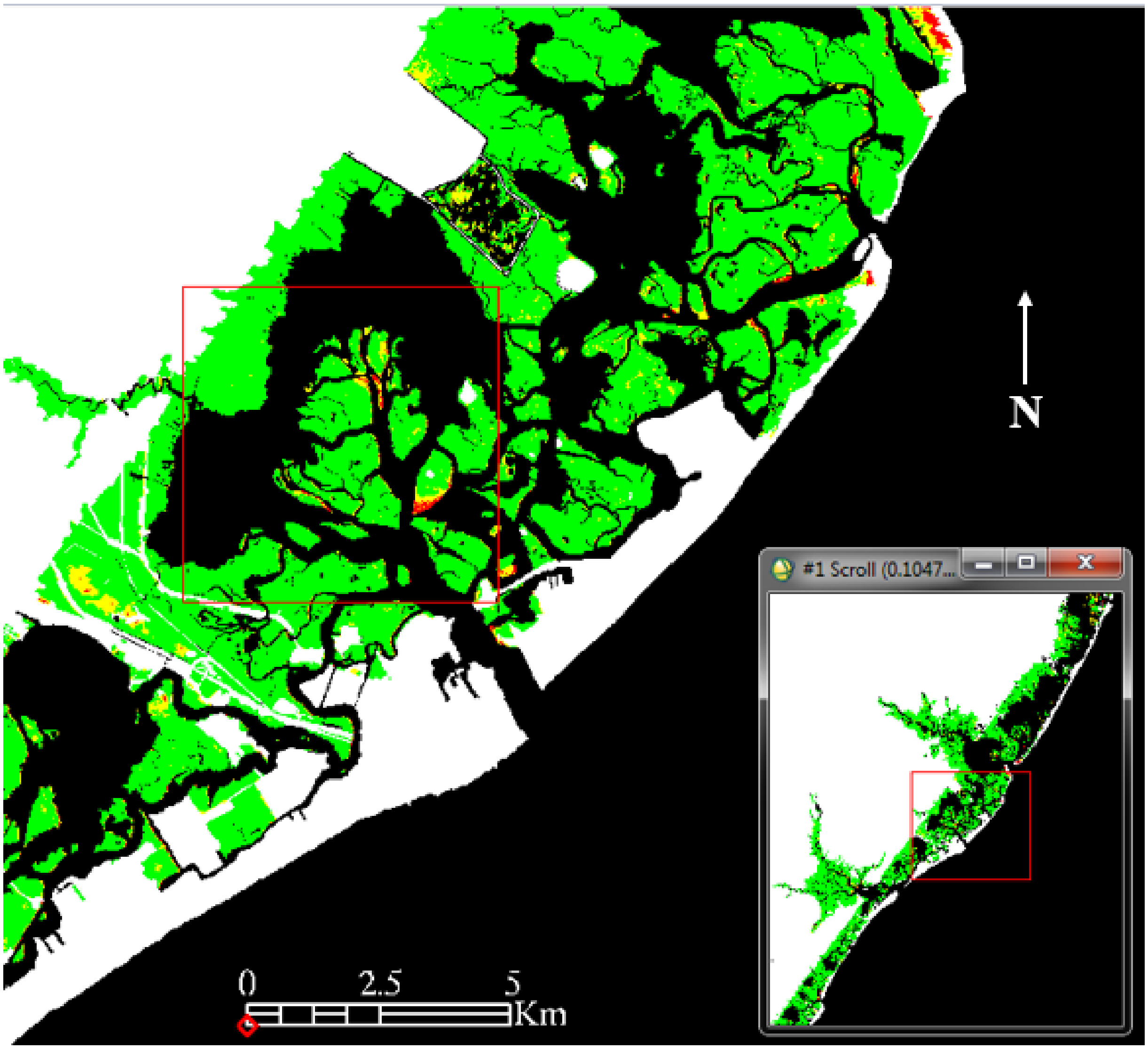

Figure 7. Marsh Surface Condition Map for the September 21, 1984 data set indicating a dominantly Category 1 marsh surface. Green pixels are Category 1 marsh containing over 40% marsh vegetation. Yellow is Category 2 marsh containing less than 40% and greater than 20% marsh vegetation. Red pixels are Category 3 marsh and contain less than 20% marsh vegetation. White is non-marsh land cover. Black is water.

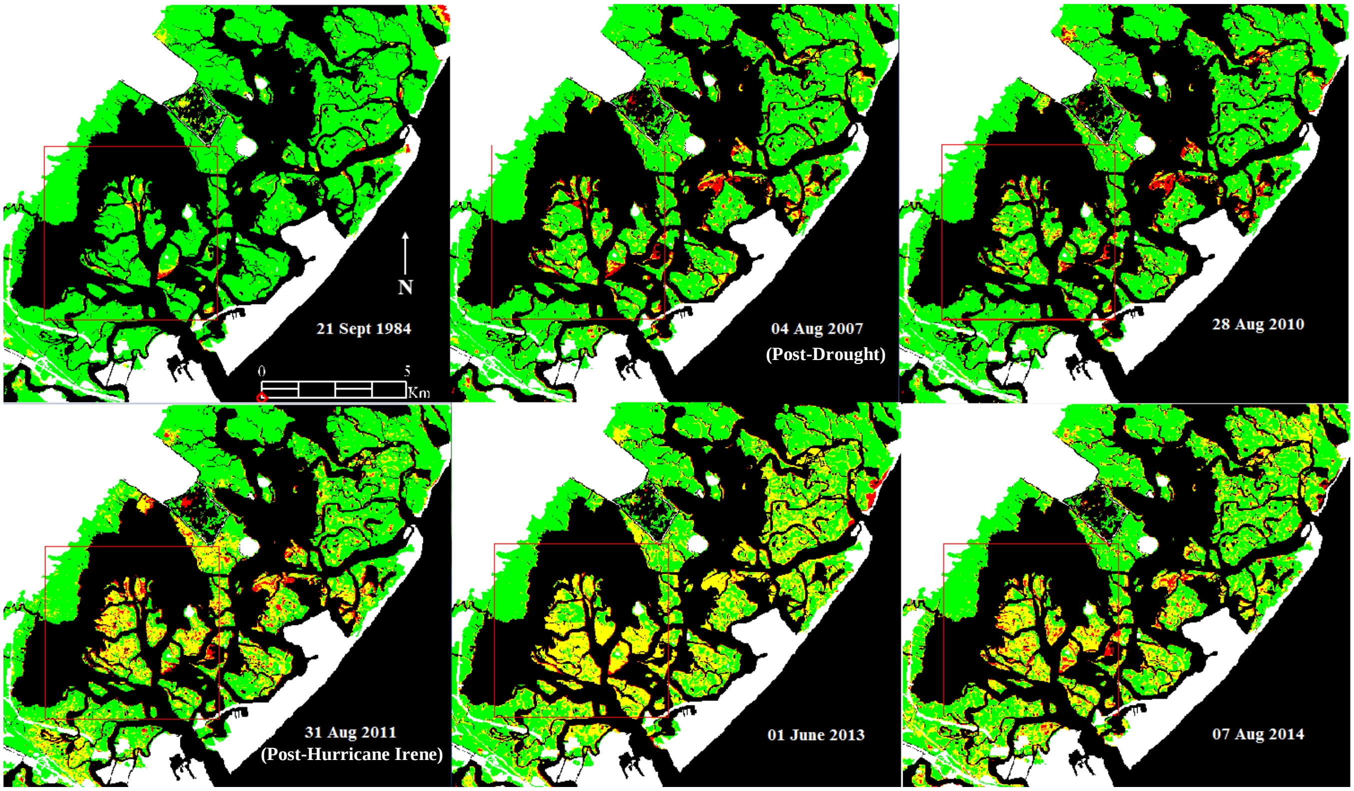

Figure 8. Marsh Surface Condition Map for six Landsat data sets (September 21, 1984, August 4, 2007, August 28, 2010, August 31, 2011, June 1, 2013, and August 7, 2014) showing changes in marsh surface condition over time near Brigantine, New Jersey. Green pixels are Category 1 marsh containing over 40% marsh vegetation. Yellow is Category 2 marsh containing less than 40% and greater than 20% marsh vegetation. Red pixels are Category 3 marsh and contain less than 20% marsh vegetation. White is non-marsh land cover. Black is water. The scale bar in the upper left map is 5 km long. The red box indicates the most Category 3 area of the marsh located nearest to where Hurricane Sandy made landfall.

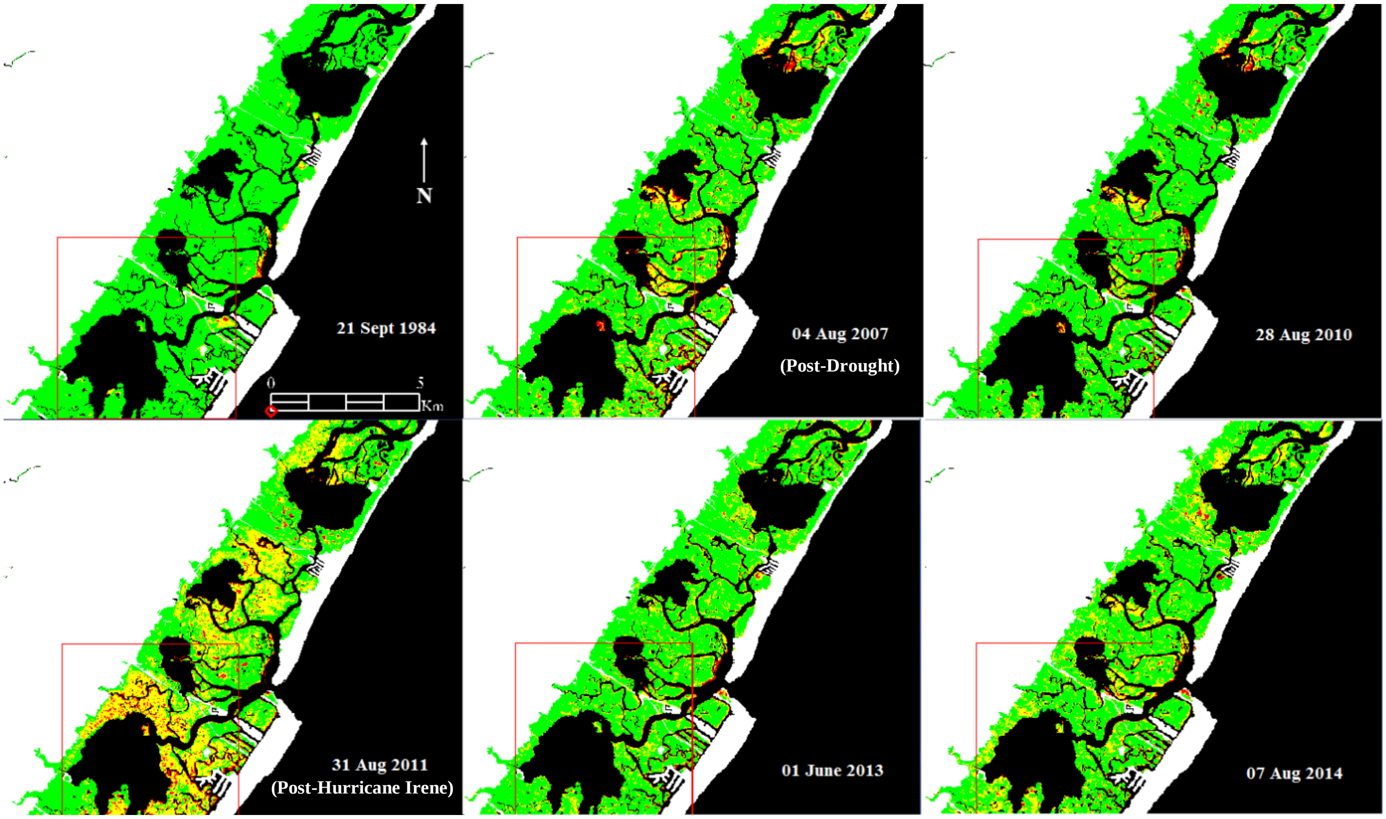

Figure 9. Marsh Surface Condition Maps for six Landsat data sets (September 21, 1984, August 4, 2007, August 28, 2010, August 31, 2011, June 1, 2013, and August 7, 2014) showing changes in marsh surface condition over time in the Townsend Inlet area. Green pixels are Category 1 marsh containing over 40% marsh vegetation. Yellow is Category 2 marsh containing less than 40% and greater than 20% marsh vegetation. Red pixels are Category 3 marsh and contain less than 20% marsh vegetation. White is non-marsh land cover. Black is water. The scale bar in the upper left map is 5 km long. The red box indicates the most Category 3 area of the marsh.

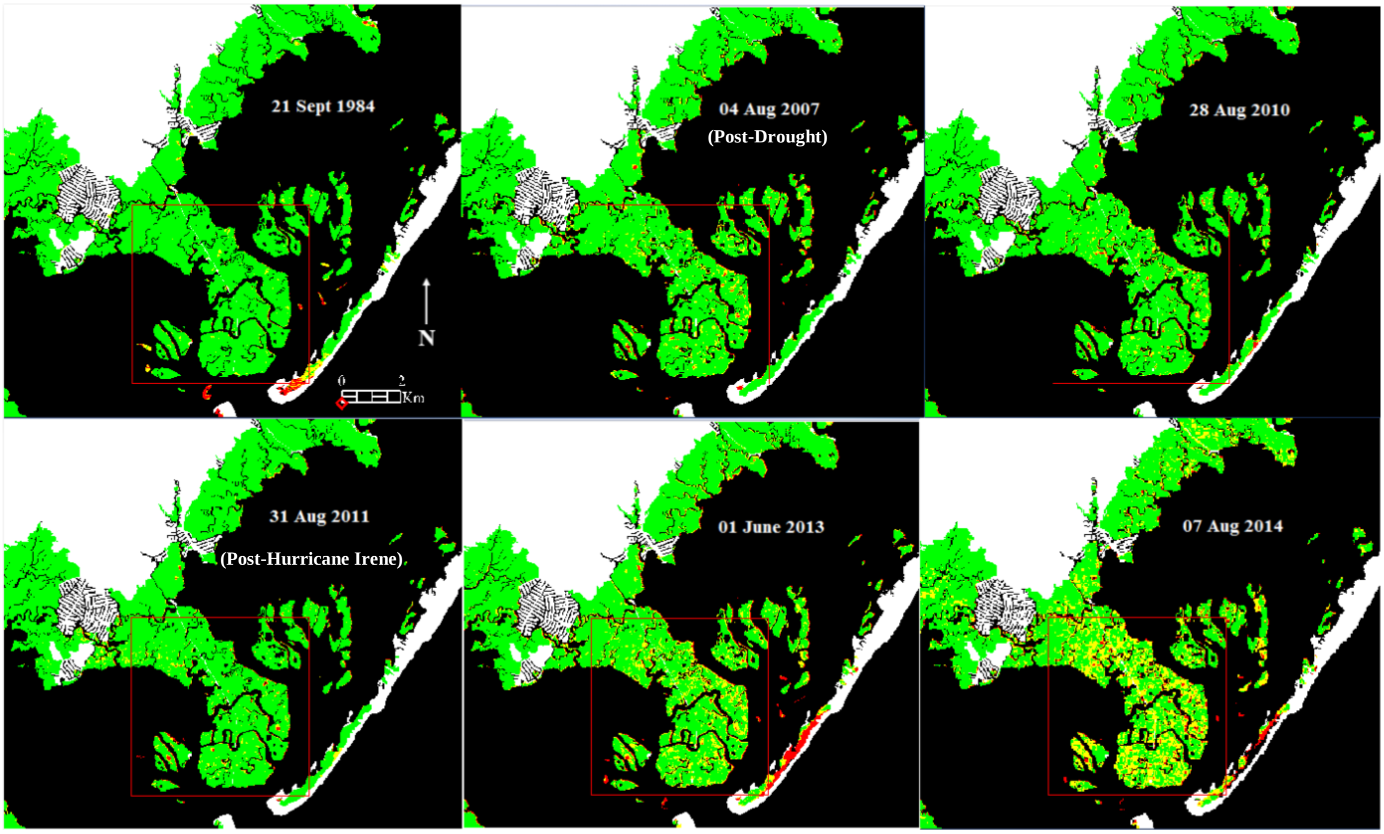

Figure 10. Marsh Surface Condition Maps for six Landsat data sets (September 21, 1984, August 4, 2007, August 28, 2010, August 31, 2011, June 1, 2013, and August 7, 2014) showing changes in marsh surface condition over time in the Tuckerton Peninsula area. Green pixels are Category 1 marsh containing over 40% marsh vegetation. Yellow is Category 2 marsh containing less than 40% and greater than 20% marsh vegetation. Red pixels are Category 3 marsh and contain less than 20% marsh vegetation. White is non-marsh land cover. Black is water. The scale bar in the upper left map is 5 km long. The red box indicates the most Category 3 area of the marsh.

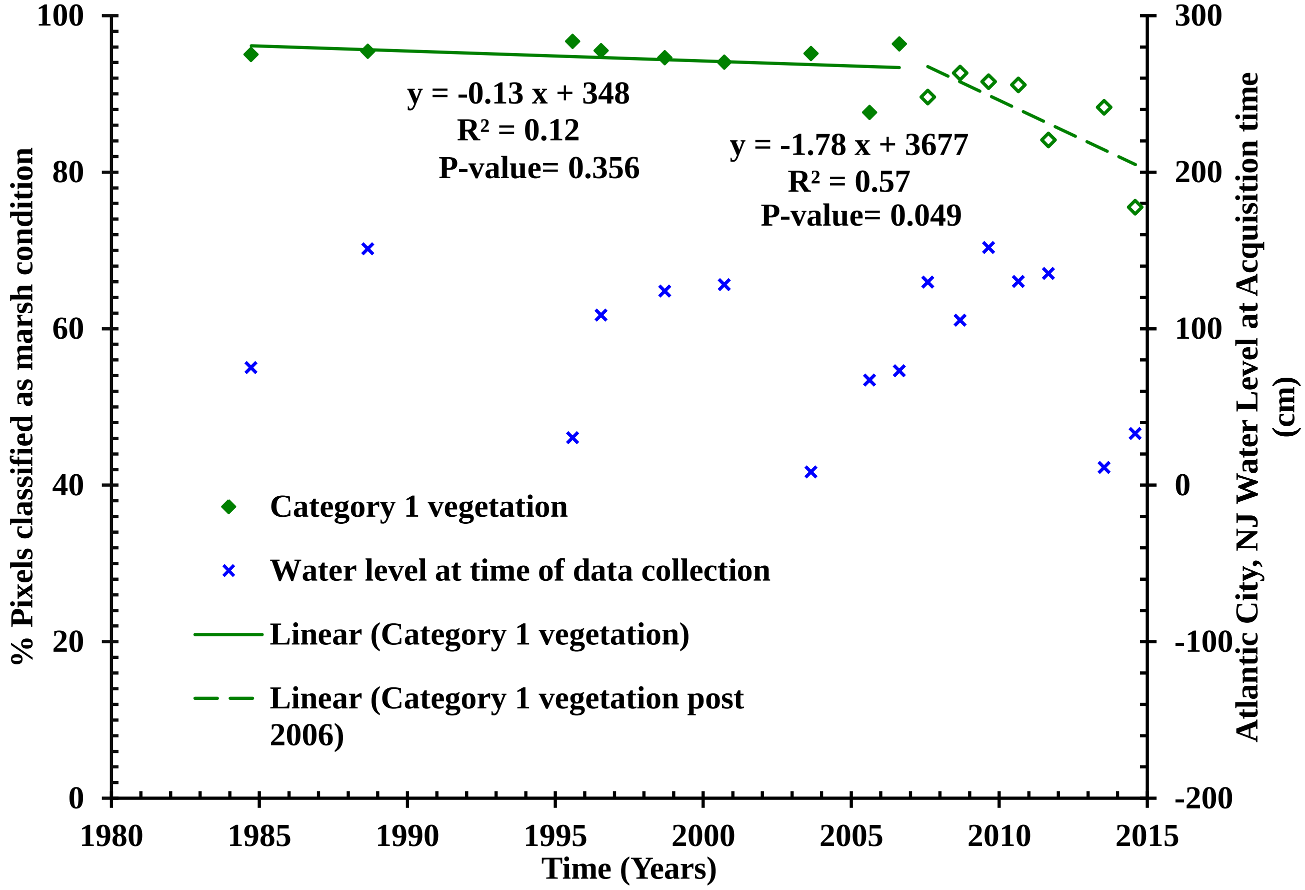

Figure 11. Variation in the percentage of pixels classified as Category 1 from Landsat TM and OLI data sets from 1984 to 2014 with trend lines. Filled green diamonds from data sets before 2007 show only a slight decrease in percentage of marsh pixels classified as Category 1 (p-value>0.05). The open green diamonds indicate a decrease in the number of Category 1 marsh pixels between 2007 and 2014 (p-value<0.05). Note that there is little correlation between the percentage of Category 1 marsh pixels and the water level measured at the time of data acquisition at the Atlantic City tidal gauge.

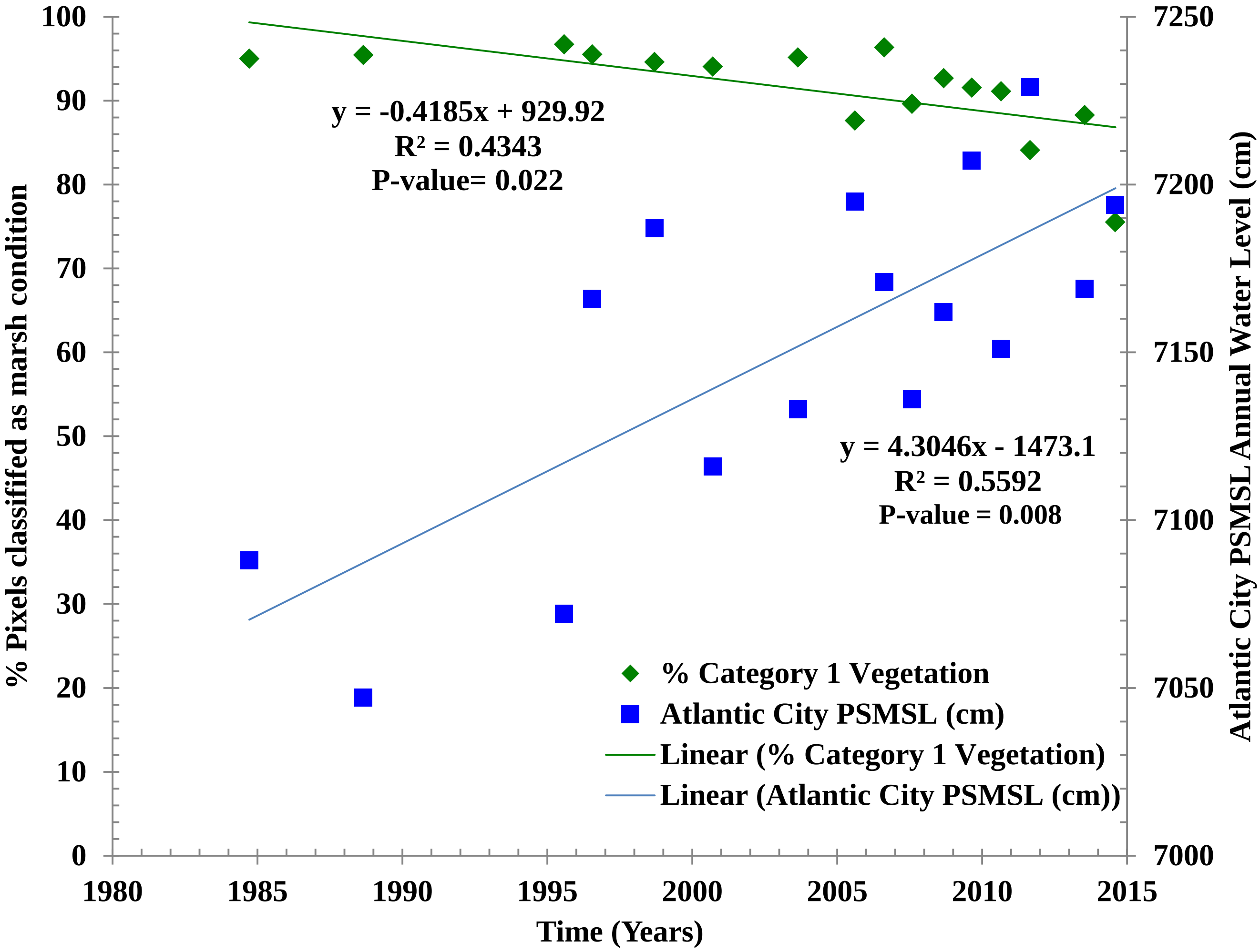

Figure 12. Variation in the percentage of pixels classified as Category 1 from Landsat TM and OLI data sets from 1984 to 2014 with a trend line and Atlantic City PSMSL annual water level (cm) compared over time. Note that there is a slightly weak correlation between the PSMSL water level (cm) (p-value<0.05) and the percent pixels classified as Category 1 marsh with a significant p-value<0.05.

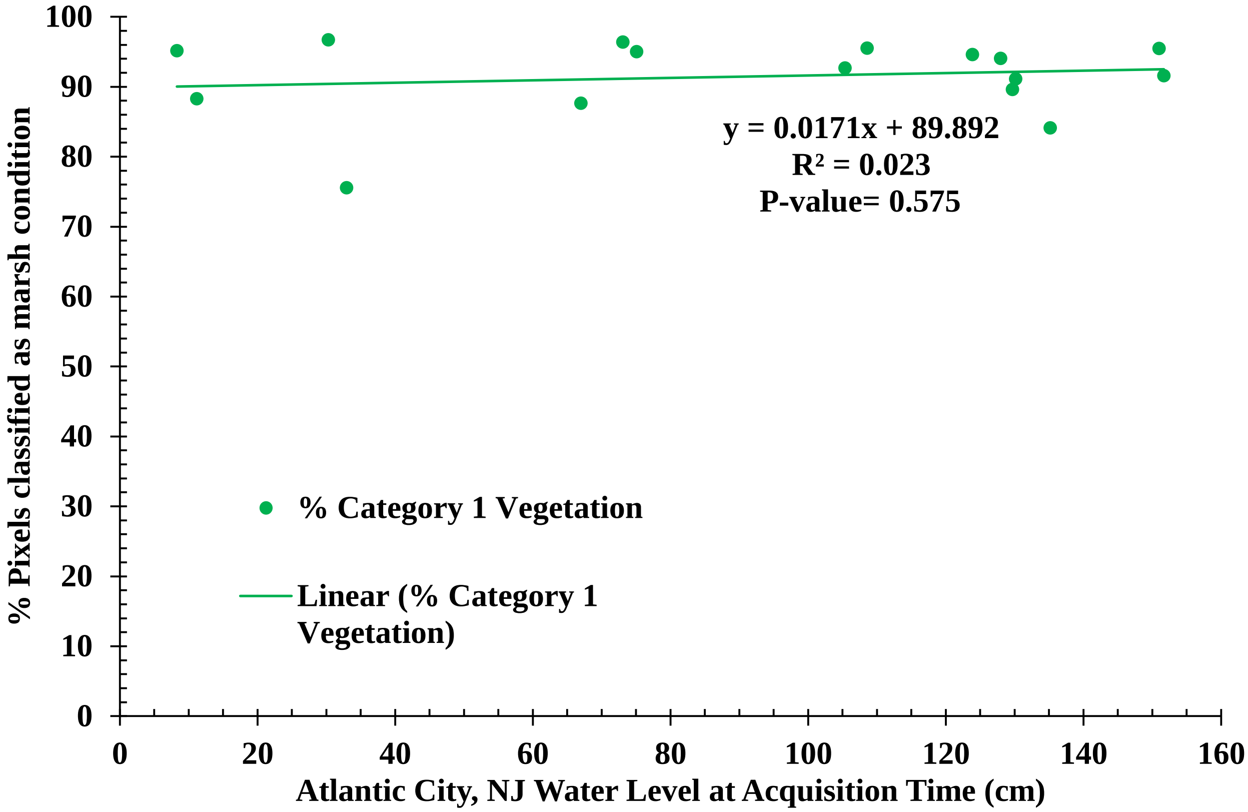

Figure 13. Variation in the percentage of pixels classified as Category 1 from Landsat TM and OLI data sets from 1984 to 2014 with a trend line compared to the Atlantic City water level (cm) at each image acquisition time (Table 2 for acquisition time).. Note that there is a very weak correlation between the Atlantic City water level (cm) and the percent pixels classified as Category 1 marsh (p-value>0.05).

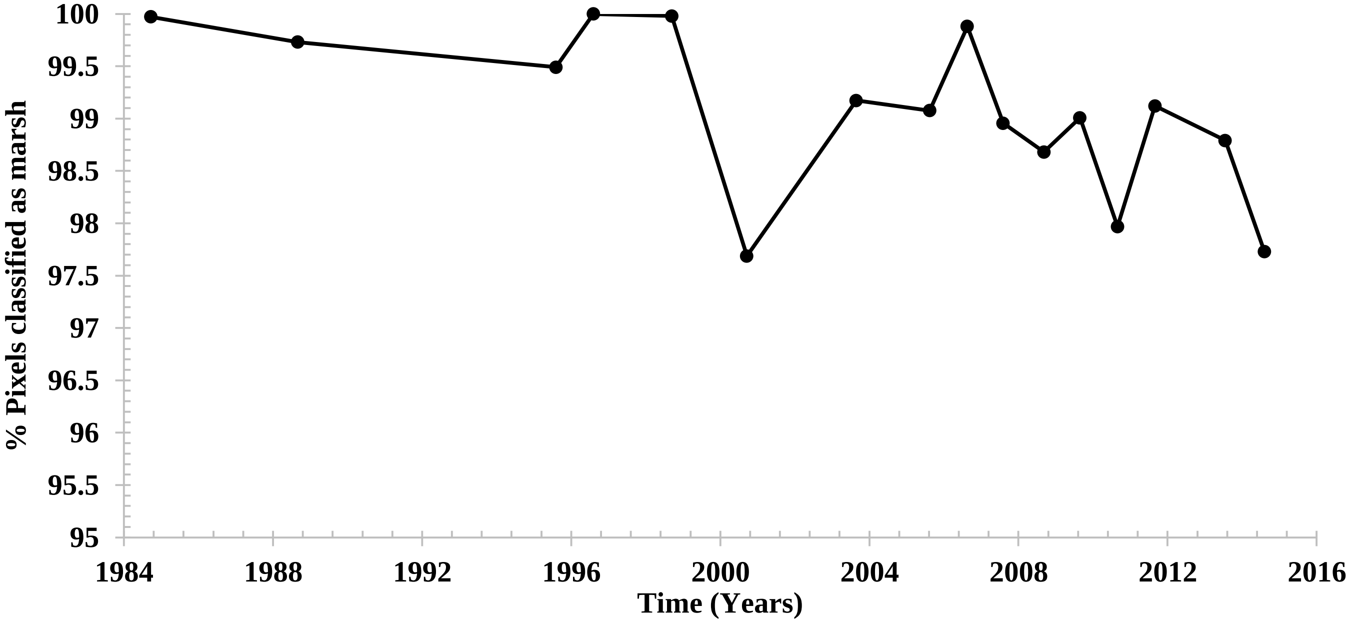

Figure 14. Variation in the percentage of pixels classified as marsh (Category 1, Category 2 and Category 3) from Landsat TM and OLI data sets from 1984 to 2014.

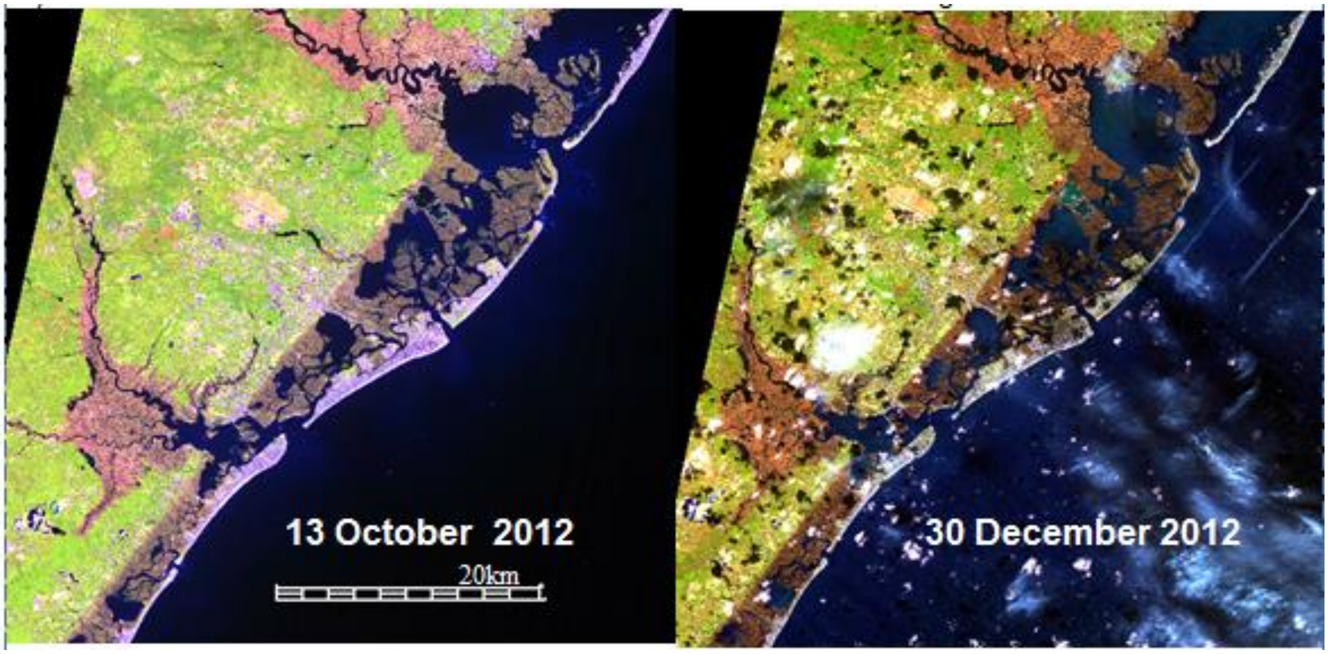

Figure 15. Comparison of October 12 and December 30 SPOT composite images illustrating the effects of clouds and cloud shadows on the December 30 image. Scale bar on the 13 October image is 20 km long. The dark brown color of the marshes on the December SPOT image indicates that marsh vegetation has senesced.

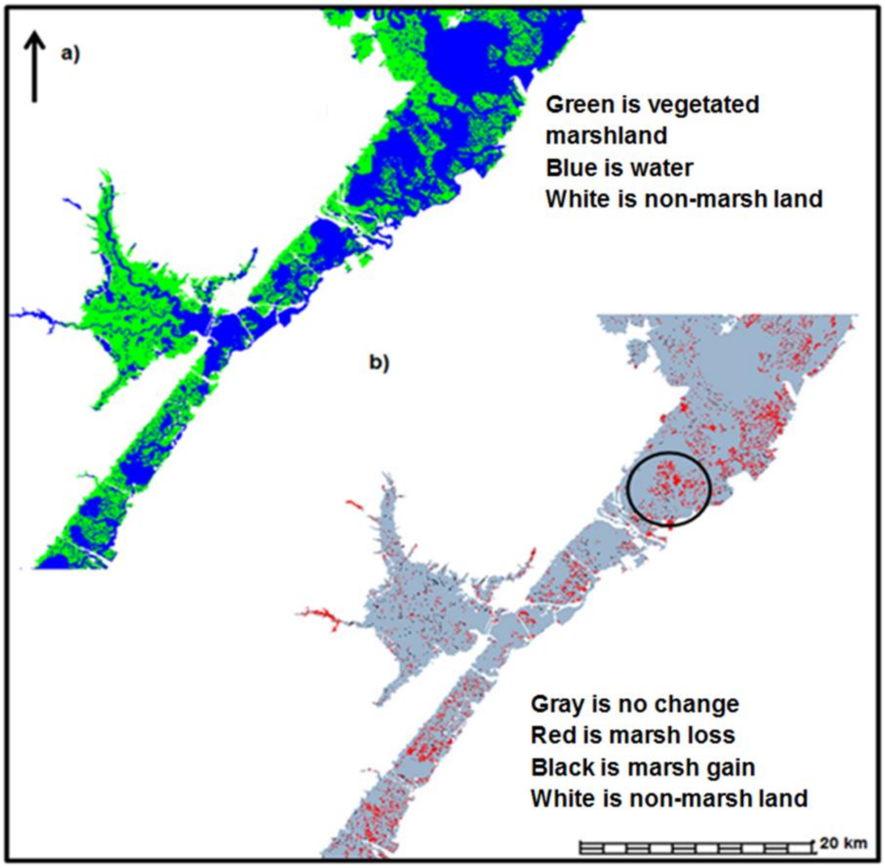

Figure 16. Comparison of classified 30 December 2012 image (a) and change detection map of the difference between the classified 13 October and 30 December 2012 SPOT 5 data sets (b). The circled area marks the location where Hurricane Sandy made landfall.

I examined whether demonstrable changes occurred in the lagoon marsh vegetation cover caused by Hurricane Sandy by comparing changes in the percent marsh vegetation cover with spectral unmixing and changes in the live and dead biomass collection data from the five New Jersey coastal marsh sites.

Satellite Study

I showed the non-statistical data (Figure 5) and examined the statistical data (Figure 6) to see if the percent pixels as Category 1 vegetation correlated with time, Atlantic City, NJ annual water level or the Atlantic City, NJ water level at the acquisition for each individual image. The

Landsat 4-5TM images of 1984 to 2006 demonstrated that the overall trend in the marshes had been one of relative stability (Figure 11) with total marsh percentage despite evidence of inter-annual and intra-annual (seasonal) variation (Figure 18). Landsat TM images from September 21, 1984 to August 31, 2011 gave insight into what the marsh area was pre-Hurricane Sandy; while Landsat 8 OLI 2013-2014 images showed the marsh area post-Hurricane Sandy with some years having multiple data sets (Figure 5). Two significant dates of 2007-0617 and 2009-0521 are labeled on the graph because 2007-0617 marked the second lowest percent of green (Category 1) vegetation due to a drought (Figure 5). Then, 2009-0521 marked the lowest green (Category 1) vegetation and the highest yellow (Category 2) vegetation as the earliest data set, before peak vegetation (Figure 5). For statistical analyses, the years with multiple data sets were limited to one data set with the marsh vegetation closest to peak vegetation. These statistical data sets for Landsat TM and OLI gave a new insight into the trend of marsh vegetation cover at or as close to peak marsh vegetation (Figure 6).

I then divided the percent vegetation results derived from the spectral unmixing of the Landsat TM and Landsat 8 OLI spectral data sets into three classes and generated Marsh Surface Condition Maps that showed the class of each marsh pixel in the lagoon marshes (Figures 7-10). Each pixel containing 40% or more marsh vegetation is identified as “Category 1” and is colored green. A pixel with less than 40% to 20% marsh vegetation is identified as Category 2 and is colored yellow. Pixels with less than 20% marsh vegetation are identified as Category 3 and are colored red.

The variations in the percentage of marsh vegetation in classified at Category 1were plotted against time in years (Figures 11). The variation in the percentage of the marsh pixels classified as Category 1 were then plotted against the average annual water level in cm for the year of data collection as measured by the Permanent Service for Mean Sea Level (PSMSL), referenced to the datum of the PSMSL (Figure 11). Lastly, the variation in the percentage of the marsh pixels classified as Category 1 were then plotted against water level in cm at the Atlantic City National Oceanic and Atmospheric Administration tide gauge at the time of the data acquisition (Figure 12).

While these data sets are shown in percentages in other figures, these data sets can also be seen in imagery. The main footprint image used is the September 21, 1984 because this is the start of the data and I focused on three areas where the marsh changed the greatest over time with the first area of change being in the Brigantine Marsh where Hurricane Sandy made landfall (Figure 7). For the next three figures, the image dates that were chosen as representative of the marsh vegetation change over time were 1984-0921, 0804-2007, 0828-2010, 0831-2011, 0601-2013 and 0807-2014 (Figures 8, 9, and 10). The greatest amount of change of Category 1 vegetation turning into Category 2 vegetation occurred in the Brigantine Marsh which was in the direct path of Hurricane Sandy (Figure 8). Farther south near the Townsends Inlet, NJ the Category 1 marsh became Category 2, but then after 0831-2011 the marsh seems to have recovered and increase in cover (Figure 9). The last major area of change was on the Tuckerton Peninsula, NJ; this area did change from Category 1 to Category 2 marsh, but at a slower pace compared to the Brigantine marsh (Figure 10).

Starting in 2007 to 2014, these Landsat TM and Landsat 8 OLI images show a trend of decreasing marsh vegetation cover (Figure 11). The percent Category 1 marsh vegetation has a moderately strong positive correlation with time from 2007-2014, while there is a very weak correlation from 1984-2006 showing marsh stability during this time (Figure 11). The percent Category 1 vegetation has a weak positive correlation with the Atlantic City, NJ annual water level (Figure 12), while the Category 1 vegetation has a very weak to no correlation with the Atlantic City, NJ water level at the individual image acquisition time (Figure 13). Overall, the total marsh did change over time, but the change was only a difference of 2.3% (Figure 14).

The SPOT 5 imagery analysis showed a decrease in marsh pixels from pre to post Hurricane Sandy through October 13th, 2012 and December 30th, 2012 comparison images (Figures 15 and16). These images suggest that the greatest marsh loss occurred in the area where Sandy made landfall near Atlantic City in the Brigantine marsh area. This area is characterized by very shallow water and low relief marshes and an increase in 0.88m water level on the post-Hurricane Sandy inundated these marshes (Figure 15). The post-Sandy Landsat imagery does suggest recovery, thus additional SPOT 5 and Landsat imagery would provide more information whether the effects of Hurricane Sandy would be lasting.

Biomass Study

The biomass study consisted of only 5 total biomass collected samples over 5 different sites. The data was primarily collected in support of Dr. Elijah Ramsey spectral radiometry research. The greatest total biomass was from the marsh study site Rainbow Island (RI live 853.99g), while the least total biomass was from the marsh study site Townsends Inlet (TI dead 74.33g; Figure 17). The only plant species that was in the collected biomass was *Spartina alterniflora* at all sites. *Spartina patens* and *Salicornia virginica* were collected only at Townsends Inlet. The biomass figure does give some insight into the differences in the live and dead biomass amounts within footprint image and the 5 collection sites were spaced evenly throughout the image, but the data is only a small representation of the entire image biomass.

The Corson's Inlet site and Atlantic City sites are similar in live biomass weight, but they differ in dead biomass which can show storm damage. The Corson's Inlet site has more dead biomass than the Atlantic City sites and this can be due to its location of being close to the New Jersey coastline and more southern than Atlantic City. The Rainbow Island site is farther inland than the other sites; this may be the reason why Rainbow Island has the largest amount of biomass. By comparison, the Townsends Inlet site is not only the closest site to the New Jersey coastline, but also the most southern site. The marsh substrate at Townsends Inlet was the only collecting site that also contained quartz sand grains. The low biomass at the Townsends Inlet site may reflect the greater amount of industrial development near this site or differences in marsh substrate. Brigantine marsh area is where Hurricane Sandy directly hit is in the satellite imagery footprint, within the biomass study sites and has a similar environment such as *S. alterniflora* and *S. patens* vegetation dominance.

Donnelly et al. (2004) conducted a study where backbarrier overwash provided a record of intense storms in the Brigantine marsh area and this gave evidence of historic and pre-historic storms striking the New Jersey coastline. The dominant plant species of the New Jersey coastline were *Spartina alterniflora* and *Spartina patens;* similarly each of our five study sites had *Spartina alterniflora* and *Spartina patens* as the dominant species. Moreover, a biomass study by Windham (2001) compared aboveground biomass of *Phragmites australis* and *Spartina patens* in the brackish tidal marshes of New Jersey. This study focused on the brackish tidal marshes of Hog Island, which is within the satellite footprint and biomass study sites. Windham (2001) found that over one growing season *P. australis* produced three times more aboveground biomass and two times more belowground biomass than *S. patens*. At the sites I examined, *S. alterniflora* and *S. patens* were out competed in some areas by *P. australis* due to their weaker plant structure, which means *S. alterniflora* and *S. patens* were highly susceptible to culm damage from storm events which would account for the low biomass weights at the Townsend Inlet site.

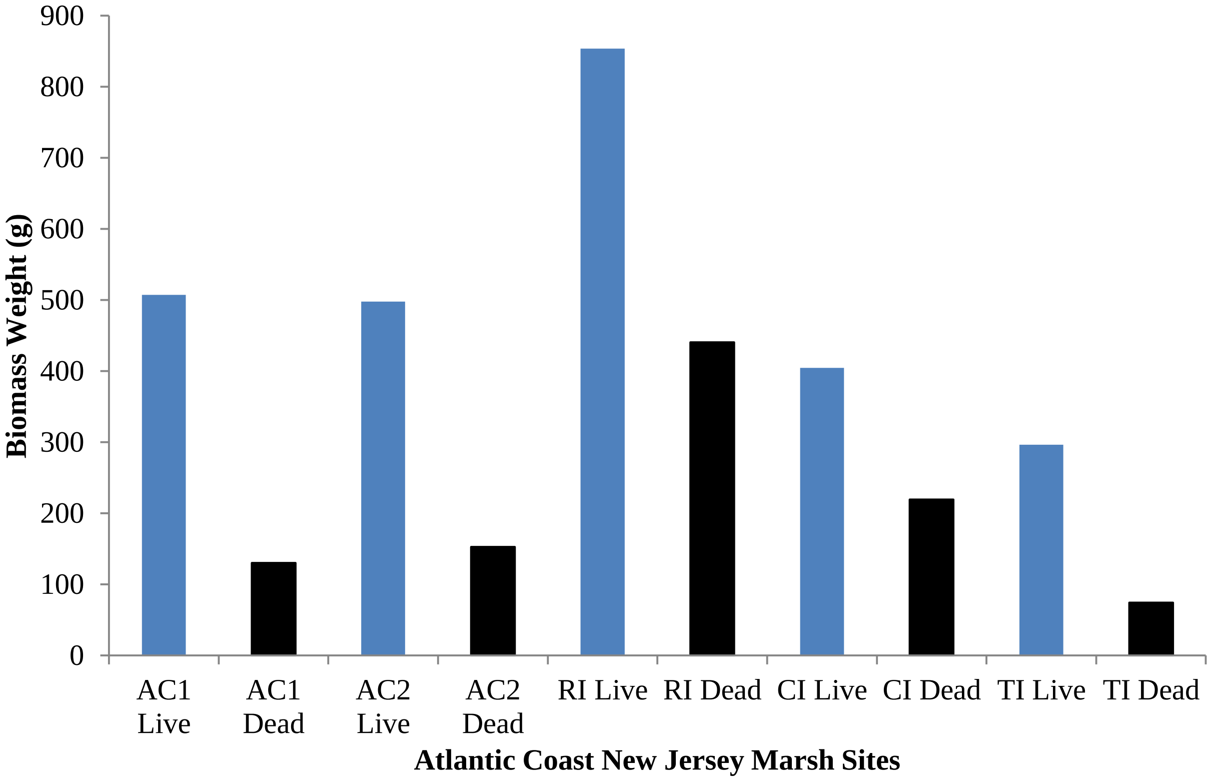

Figure 17. Atlantic Coast New Jersey salt marsh live and dead biomass weight from 5 different sites along the coastline. Mean +/- SE. T-Test p-value= 0.261.

Chapter 5: Discussion

The degree of inter-annual variability in summer and fall vegetation cover in the salt marshes of the New Jersey coastline is surprising, even considering the amount of anthropogenic industrialization and preexisting degradation of the marsh vegetation in certain areas. In this study, Hurricane Sandy was seen to have a moderately negative effect on the New Jersey Atlantic coastal marsh vegetation through Landsat and SPOT 5 satellite imagery analysis and biomass study. I argue that this negative effect is compounded with negative effects from previous storms and other processes. The Landsat 4-5 TM and 8 OLI imagery data also indicate interannual and seasonal variability within the coastal marsh, before and after when Hurricane

Sandy made landfall (Figure 18). There is a gap in the Landsat data between November 2011 and April 2013 due to the satellites failure due to a rapidly degrading recording component starting in November 2011. Yet, the 1984-2011 Landsat imagery does show changes in marsh vegetation.

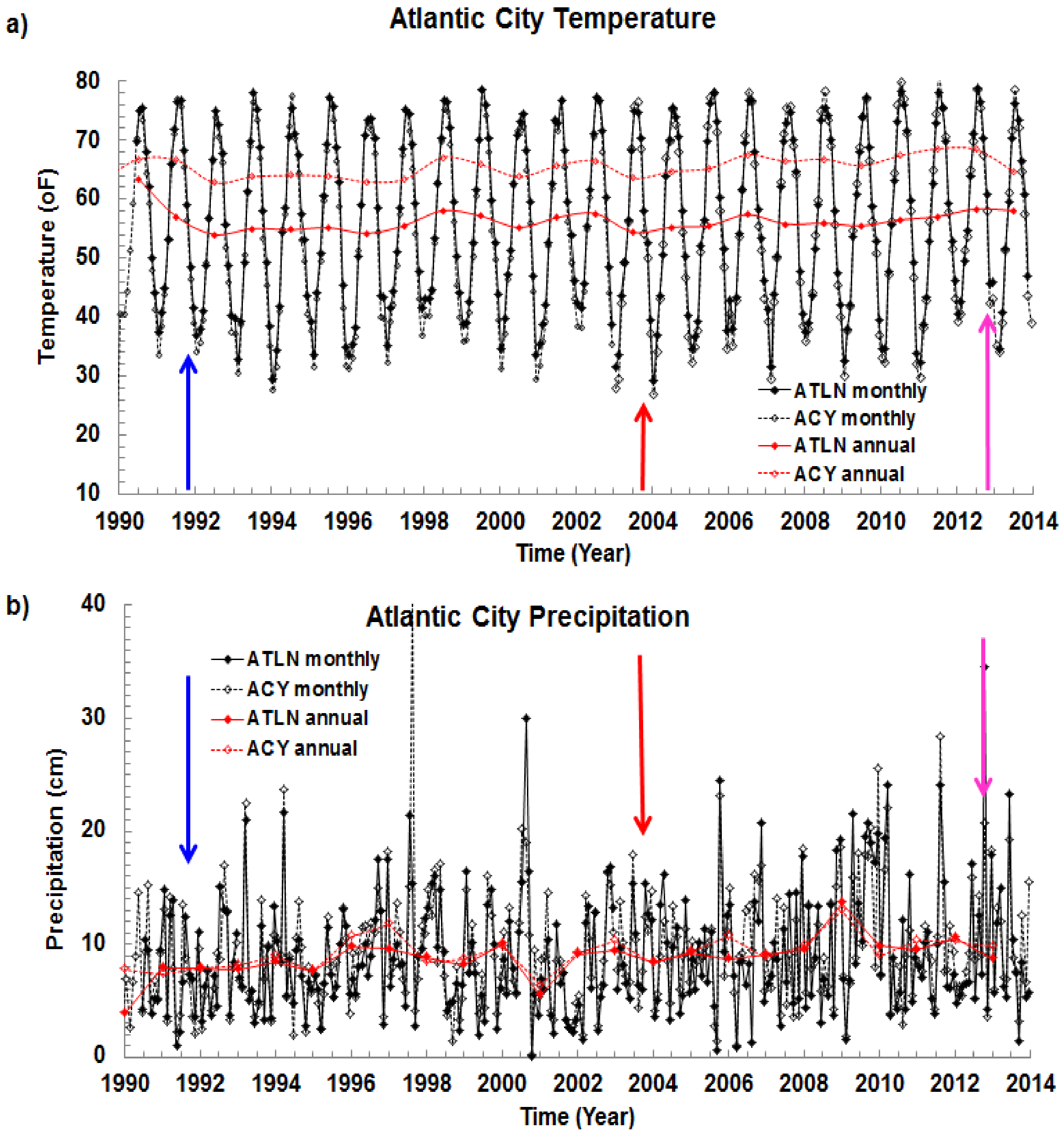

Figure 18. Temperature (a) and precipitation (b) data from the Atlantic City International Airport weather station #93730 (ACY) and the NOAA weather station #13724 (ATLN) from National Climate Data Center (2014). Locations of the two weather stations. Blue, red, and magenta arrows mark the “Perfect Storm”, and Hurricanes Isabel and Sandy.

Spectral Unmixing Data

The marsh surface condition index (MSCI) color categorized Landsat images measured vegetation indices which showed on overall 17% increase in Category 2 (yellow) marsh from the 1984-0921 images to the 2014-0807 images with some changes over time (Figure 6). This increase in Category 2 marsh, with a decrease in Category 1 (green) marsh suggests there was not an increase in Category 2 marsh becoming Category 3 (red). This decrease in marsh vegetation cover (green to yellow) seemed to occur because of previous harsh storm impacts combined with long term anthropogenic impacts or relative sea level rise.

Large-scale human activities like canal construction in Louisiana (Turner, 1997); have resulted in a high rate of marsh loss compared to outright loss of coastal marshes (Couvillion et al., 2011). More recently, the phenomenon of coastal eutrophication as an indirect human impact has already been linked to decline in fisheries and SAV (Waycott et al, 2009), and has been linked with making marshes more susceptible rapid sea level rise and storms (Najjar et al, 2000). Rapid sea level rise is hard to predict because global climate change will not only affect the speed of sea level rise, but it can also affect hurricane and tropical-storm characteristics. Projected rising sea level alone can also amplify the impacts of hurricane-attendant storm surges (Raper, 1993). The ability of coastal wetlands to migrate landward as sea level rises and salt water intrudes the coastal zone will be compromised significantly by human modifications, including the construction of bulkheads and river-flow management to reduce sedimentation (Titus, 1988).

Pervious storms that occurred between 1984 and 2003 have been documented as causing vegetation damage with strong waves and beach erosion, but all of these hurricanes occurred in September or later, as the vegetation was starting senescence. The storms that caused the most damage started in 2003 with Hurricane Isabel. Hurricane Isabel caused a storm surge of up to

3.2 meters in height and the persistent strong wave severely eroded the coastline (Table 1). While Hurricane Isabel also occurred in September, it can be seen as a start to the intensity of storms gradually increasing over time (Michener et al, 1997).

The Category 1 vegetation pixels started to decrease progressively starting pre-Hurricane Sandy in August 2007 through post-Hurricane Sandy in August 2014 (Figure 11). In the summer of 2007, there was a large drought and caused the marsh to die off and some areas to go into early senescence leading to a drop in percent Category 1 marsh (Kearney and Riter, 2011). After 2007, the marsh stayed relatively stable at this lower percent (~85%) of Category 1 vegetation (Figure 11). In 2009 Hurricane Bill, a category 1 hurricane did create strong waves as high as 4.6 m and severe beach erosion (Table 1 and Figure 1). Hurricane Bills' high wave heights created the highest water level of 151.7 cm for the August 25, 2009 image at acquisition time compared to all the processed images. This high water level was possibly caused by not only the increased wave heights, but also the increased precipitation due to Hurricane Bill. These high waves also created salt inundation of the coastal marshes. This saltwater influx into the marshes potentially leads to elevated salt levels which makes it difficult for plants to take up water, increases water stress and reduces growth of marsh biomass. This decrease in marsh biomass can be seen in the percent pixels of Category 1 marsh as these pixels decrease and the Category 2 vegetation pixels increase over time (Figure 6).

One of the most damaging pre-Hurricane Sandy storms that impacted the New Jersey coastal marshes and caused a drop of almost 10% in Category 1 percent vegetation in the August 31, 2011 image was Hurricane Irene (Figure 11). Hurricane Irene caused major flooding in the entire coastal area including the marshes for up to 3 days after the initial landfall and wave heights up to 9.9 m which broke the previous wave height records for New Jersey (Table 1).

These large wave heights and lasting flooding can be seen in the water level of 135.18cm for the August 31, 2011 image acquisition time (Table 2). This water level is one of the highest for all the processed images and this high water level mainly due to flooding can cause enlargement and formation of interior ponding within the coastal marshes. Ponding and marsh vegetation cover loss can be seen in the Brigantine Marsh and in the marshes near Towsends Inlet (Figures 8 and 9). Newly formed ponds can be created through high volumes of rainfall in combination with wetland or marsh loss which can be due to saltwater inundation and marsh biomass loss (Morton and Barras, 2011). Enlargement includes erosion of pond perimeter, removal of wetlands within a pond, and coalescing of adjacent ponds. Both perimeter and interior pond expansion can involve erosion of the pond banks or compression of mats of floating vegetation. Pond expansion is normally a permanent loss of wetlands that remains as a legacy of individual or cumulative storm impacts on the delta-plain surface erosion and can affect surface accretion rates (Harris and Chabreck, 1958). This is one factor that explains the post Hurricane Sandy decrease in percent Category 1 marsh.

Post Hurricane Sandy percent Category 1 marsh vegetation increase slightly in 2013, but this can be due to temporal and seasonal variability; especially since the percent Category 1 vegetation then decreased by 10% in 2014 while being at peak vegetation and there was a 7% increase of Category 2 vegetation. This steadily decreasing percent Category 1 marsh vegetation from 2007 is supported by a moderately strong positive correlation between percent pixels of Category 1 marsh and time and having a significant p-value (Figure 11). While this same correlation was done for images between 1984 and 2006, there was a weak positive correlation showing the marsh being relatively stable. Time seemed to be the main factor when it came to changes in marsh cover, but I also saw if the PSMSL Atlantic City annual water level and the

Atlantic City water level at acquisition time also had correlations with marsh vegetation cover (Figure 12 and 13). Overall, neither water level (annual or acquisition time) had a high positive or negative correlation with marsh vegetation cover. The PSMSL (Permanent Service for Mean Sea Level) data had a weak positive correlation (Figure 12), but this is a significant correlation and the Atlantic City water level at acquisition time had a not significant, very weak positive correlation with marsh vegetation cover (Figure 13) supporting that the main factor that correlated with changes in marsh cover was time; for my study, time was over years at peak vegetation.

The total marsh percentage (Figure 14) varying slightly year to year with the MSCI percentages decreases occurring when storms have been documented (Table 1) supports the idea that storm impacted vegetation will have higher percentages of Category 1 marsh becoming Category 2 instead of Category 2 marsh becoming severely Category 2. Also, the temporal and spatial variability in the total marsh vegetation could be due to seasonality and other climate factors. These factors would affect the total marsh vegetation percentages over time, which accounts for the small variability in marsh stability pre-Hurricane Sandy. The total marsh percent does have a decrease of only 2.3%, but there is a decreasing trend and this trend is sure to continue as the frequency and intensity of storms along the New Jersey coastline increase. The percent total marsh is seen well through the spectral unmixing imagery.

Landsat Imagery

The base image for my study is the September 21, 1984 because it is the start of the data set and has close to the highest amount of percent Category 1 marsh (Figure 11); this base image includes the footprint image and focuses on the area where the most marsh change was seen.

This area know as part of the Brigantine Marsh, was in the direct path of Hurricane Sandy as it made landfall in 2012. To show the marsh change over time six images were chosen because they best represented the timeline with the marsh being stable between 1984 and 2006 and starting to degrade with the drought in 2007 and then degrading more between 2010 and 2014. The area that first showed the most change was within the Brigantine marsh because there was change of Category 1 marsh becoming Category 2 (green to yellow colored) as well as Category 2 marsh becoming severely Category 3 and in danger of not recovering (yellow to red colored) (Figure 12). The 2007 image contains more Category 3 marsh compared to any of the other pre-Hurricane Sandy images and I believe this is because of the drought that occurred during the summer because in 2010 some of the Category 3 marsh areas do recover and become only Category 2 in 2011.

Post Hurricane Sandy, the Brigantine marsh vegetation in the 2013 image did have some recovery in the damage marsh, but this can be due to seasonal variation because the Category 3 vegetation stayed Category 3 and did not recover by 2014. Instead, by 2014 the Category 3 marsh increased, but the change from Category 1 marsh to Category 2 marsh increased greatly by over 10% (Figure 8). This damage can occur because of a variety of hurricane impacts, but mainly I believe the combination of storm surge, high winds and excessive precipitation caused the most damage to marsh vegetation. Also, the degradation of the marshes in the Brigantine marsh would have been on a larger scale due to being in the direct path of Hurricane Sandy. Supported by the examination of two other Category 2 areas with in the New Jersey marshes, I can see that the Brigantine marsh area did have the largest decrease in percent Category 1 marsh over time and post Hurricane Sandy (Figure 8).

The examination of a second marsh area farther south within Townsends Inlet, NJ revealed the marsh area had experienced similar degradation pre Hurricane Sandy to the Brigantine marsh, but differed post Hurricane Sandy (Figure 9). Similar to the Brigantine marsh, the 2007 image shows signs of degradation which can be because of the summer drought and this degradation continued to where the marsh shows the most degradation in 2011. The 2011 depredation is so great because of the previous decrease in Category 1 marsh and the impacts of Hurricane Irene. Yet, in 2013 the marsh looks to have recovered mostly with some areas along the tidal creeks closest to the coastline that was Category 2 in 2011 now becoming Category 3 in 2013. Then in 2014, there was a decrease in percent Category 1 marsh with some of the Category 2 marsh becoming Category 3 (Figure 9). The Townsends Inlet marsh area was not where Hurricane Sandy made landfall, but did experience Hurricane Sandys' offshore impacts such as high wave heights and severe winds. Since this area is also more developed because it's more southern, the marshes may have adapted more to stressful conditions by having a high salt tolerance or adapted to changes in water level. In comparison, the examination of a third marsh area which is located north of Hurricane Sandy's landfall area is the Tuckerton Peninsula, NJ.

The Tuckerton Peninsula marsh has been experiencing slowly degradation marsh vegetation as seen in the Landsat imagery from 2007 to 2014 (Figure 10). The percent Category 1 marsh has slowly been changing to Category 2 marsh in certain areas of the peninsula, but is most noticeable post Hurricane Sandy. From 2011 to 2013, there is a noticeable increase of percent Category 1 marsh becoming Category 2 closer to the coastline and the marsh behind the barrier island changed from Category 1 to severely Category 2 marsh (Figure 10). The marshes area directly behind the barrier island becoming severely Category 2 is not surprising because the barrier islands were the first line of defense for the New Jersey coastline when Hurricane Sandy made landfall. Yet, the peninsula marshes also Category 3 more post Hurricane Sandy compared to any other storm. The degradation observed from 2013 to 2014 shows that the marsh may not have been able to recover from Hurricane Sandys' impacts such as salt inundation because the Category 2 marsh does not recover to Category 1 vegetation from 2013 to 2014. Instead, the marsh vegetation that was Category 2 became severely Category 2 and areas where there was Category 1 vegetation in 2013 became Category 2 in 2014 without any strong storm impacts from 2013.

Validation

The results of the biomass study (Figure 17) in combination with the SPOT 5 10 m^2 resolution change detection image showing an 8% decrease in marsh after Hurricane Sandy revealed that the Brigantine marsh had the most marsh vegetation damage, which confirms the spectral unmixing results for the same area. Biomass study sites of Atlantic City 1&2 are at the southern end of the Brigantine marsh and did experience vegetation cover loss. While the AC 1&2 live and dead biomass weights were not the greatest and least amounts of either biomass, the sites were almost as far inland as Rainbow Island, but were closer in their amount of biomass to TI (least for both live and dead biomass). AC 1&2 field sites are also located near where the 8% marsh loss (Figure 16), with only Absecon channel separating the two marsh patches. Because the AC 1&2 sites were in the direct path of Hurricane Sandy, they experienced more storm impacts than any of the other field study sites and the impacts were seen as marsh damage in the SPOT 5 change detection.

The biomass collection occurred at the end of September when the plants starting senescence, which is also near the time, when Hurricane Sandy hit. Since Hurricane Sandy made landfall in late October 2012 the storm impacts affected marsh biomass as the plants were likely senescent. Hurricane Sandy would have less effect on the marsh vegetation during senescence because the plants are gradually decreasing their ability to divide cells and grow. This decrease in growth rate means the plant damage from the storm effects would only affect the plants of the 2012 growing season compared to the plant growth of the following years growing seasons. During the biomass collection, there were a number of field observations including the already discussed dominant species of *S. alterniflora*. The disturb areas that had more dead biomass cover included areas of low marsh and increased salt inundated soil areas. Other areas of disturbance include areas of ponding or enlargement of tidal creeks. This enlargement of water bodies leads to marsh shoreline erosion and can lead to salt inundation in high marsh areas. Biomass collection needs to be done near or at peak vegetation to fully understand where disturbances have occurred and what vegetation has been affected by disturbances. During peak vegetation time, biomass can be seen as live or dead with more certainty due to disturbances such as salt inundation or erosion compared to being dead due to senescence.

Implications

The spectral unmixing results being validated by the 2014 marsh biomass study and the SPOT 5 image change detection demonstrates the impact that pervious hurricanes and Hurricane Sandy had negative impacts on the New Jersey coastal marshes. The main hurricane impacts that caused marsh degradation were large storm surges, high wind speeds and excessive precipitation. These impacts caused salt inundation, enlargement and formation of interior ponds and shoreline erosion of the New Jersey coastal marshes. Salt inundation within the marshes occurs because the strong storm surge brings in massive amounts of concentrated salt water which stresses the marsh vegetation and if prolonged for too long, the vegetation can cause salt burn. Salt burn occurs mainly in areas where plants grow in poorly drained soil areas or in areas where runoff collects. The Brigantine marsh becomes a large water collection area when the combination of storm surge and excessive precipitation occurs at the same time making it difficult for water to drain. With the coastal marshes not being able to drain quickly or flush out runoff means the enlargement or formation of ponding within the marshes can easily occur. The stagnant water within the marsh can remove sediment and loosen the edge marsh vegetation making it easier for shoreline erosion to occur. This loss of sediment and marsh vegetation leads to enlargement of ponds and formation of new ponds within the coastal marshes.

Chapter 6: Conclusions

This study of these effects of Hurricane Sandy on the New Jersey Atlantic coastal marshes exhibited that: (1) the biomass between the New Jersey coastal marshes is similar to other Atlantic coastal marshes; (2) the marshes were relatively stable between 1984-0921 and 2006-0817 with some decreases due to water level and seasonality; (3) there was a steady decrease in marsh vegetation cover from 2007-0804 to 2014-0807; (4) there was an 8% decrease in marsh vegetation cover after Hurricane Sandy and (5) the majority of the New Jersey marsh vegetation decrease on the MSCI images was Category 1 (green) marsh becoming Category 2 (yellow), not Category 2 marsh becoming severely Category 2. These marshes, unlike the Louisiana coastal marshes, have had different storm impacts due to the storm type.

The New Jersey marshes are mainly only impacted by low category hurricanes and winter nor’easters with large storm surges. The impact of Hurricane Sandy was unlike any storm that previously made landfall on the New Jersey coastal marshes due to its storm surge, high wind speeds and duration of excessive precipitation. While the stability of the marshes stayed consistent through various storms, there was still a significant decrease after 2007 to post-Hurricane Sandy in percent Category 1 marsh and percent total marsh percentage that was not seen after other storm events. This shows that Hurricane Sandy storm impact on the marsh vegetation has lasted after the initial impact. Hurricane Sandy had a moderately negative impact on the New Jersey coastal marshes and only the further studies will show how long Hurricane Sandy's impact will last.

Chapter 7: Future Studies

One limitation of this study is that the research was based on 30-m resolution Landsat imagery data. Although this resolution, both spatially and temporally, enabled a regional interpretation of vegetation changes, it is suggested that future research focus on the actual species distribution. A more comprehensive study of the on-the-ground biomass and their respective tolerances to environmental change, especially change in salinity. This knowledge would add to our study and would in understanding how spatial patterns enable determination of relationships between hurricanes and coastal vegetation dynamics. The implications for assessing marsh sustainability relative to future increases in sea level rise can be significant; especially since the level of Atlantic hurricane activity has recently increased and is expected to continue for the next several years. The intensity of future Atlantic hurricanes is also expected to increase over time (Michener et al, 1997). Also, human alteration of wetlands and the surrounding landscape may increase rates of response to climate change or totally overwhelm such responses. Activities such as groundwater pumping and other industrious development can bring about a very much accelerated rate of local relative sea level rise.

Future studies will need to look outside of this study’s footprint area, which includes the entire New Jersey coastline. Seeing the effect of Hurricane Sandy on the New Jersey coastal salt marshes outside of Hurricane Sandy’s direct path will give a new viewpoint on the intensity of the storm and it’s after effects. The coastal marshes change along the New Jersey coast moving from North to South because the amount of development and the shape of the coast changes. The northern marshes are called the New Jersey meadowlands because of the vast amounts of *S. patens* (salt marsh hay) while the southern marshes are more of a lagoon system with barrier islands and back barrier marshes. These key salt marsh differences mean there could be differences in reactions to storm impacts, especially over time.

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