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ORIGINAL RESEARCH

Quantification of Impacts and Ecosystem Services Loss in New Jersey Coastal Wetlands Due to Hurricane Sandy Storm Surge

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Abstract The effects of Hurricane Sandy storm surge on wetland degradation and consequent loss of ecosystem services were estimated for coastal wetlands in New Jersey. Research in this field has qualitatively determined the effects of hurricanes on wetlands; however, there has been little quantification of wetland degradation and absolutely no assessment of impact to ecosystem services following a hurricane. Wetland degradation was mapped and quantified by comparing pre- and post-Sandy aerial photography from 2012. Loss of ecosystem services was estimated based on degree of wetland degradation. Our wetland degradation analysis found that the main mechanisms behind degradation were erosion, deposition and marsh salinization. Moderate flooding and marsh dieback were the most prevalent types of damage, and saline marshes and herbaceous wetlands were the most degraded wetland types. Severe degradation was most prevalent, occurring in 41.38 % of the wetlands. In addition, we found that 51.05 % of the degradation was long-term damage. In our ecosystem service loss analysis, we created a range of monetary values to show the distribution of damage. Monetary loss within New Jersey ranged up to \$4.4 billion of the total \$9.4 billion provided by wetlands (47 %). Our wetland degradation quantification and ecosystem service loss analysis provide insight into the impacts from storm surge damage and offers a novel methodology for remediation and restoration efforts.

Keywords Coastal wetlands · Ecosystem services · Hurricanes · GIS · Storm surge · Aerial photography

Introduction

Hurricanes are known to cause tremendous disturbance, degradation and anthropogenic damage to areas in their path (Morton and Barras 2011). As the frequency and intensity of hurricanes, tropical storms and cyclones are forecasted to increase in years to come due to global climate change (Emanuel 2005; Trenberth 2005; Webster et al. 2005; Edenhofer et al. 2014), there is an increased need to understand and quantify the damage done to wetlands as a result of storm surge. It is well known that hurricanes' high velocity winds and associated waves and storm surges cause damage (e.g., shoreline erosion, flooding and property loss) that can cost millions of dollars to repair (Doyle 2009). Preliminary damage assessments indicate that Hurricane Sandy was the second costliest cyclone nationally with \$50 billion in damage costs (Blake et al. 2013). More than 650,000 homes were damaged or destroyed, and 8.5 million people were without power, (Blake et al. 2013), underscoring the strength and breadth of storm surge across New Jersey's coastal and inland areas.

Ecosystem services are the benefits that humans receive via ecological function either directly (e.g. recreation) or indirectly (e.g. water quality) from a given type of ecosystem (Costanza et al. 2014; Millennium Ecosystem Assessment 2003). Typically land managers use ecosystem services to assess the value of an ecosystem and allocate resources efficiently (Woodward and Wui 2001; Troy and Wilson 2006; Li

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et al. 2014; Scolozzi et al. 2014). The power of utilizing ecosystem services, which are commonly in monetary units, is that they act as a common language and can reveal important social benefits that could potentially be hidden (de Groot et al. 2002; Troy and Wilson 2006; Euliss et al. 2008). Specifically wetlands provide services including but not limited to: wildlife habitat, coastal erosion protection, water purification and regulation, nutrient cycling, and recreation (Woodward and Wui 2001; Costanza et al. 2006). Most applications of wetland ecosystem services determine the change in ecosystem services due to land use change (Nelson et al. 2009: Goldstein et al. 2012; Bateman et al. 2013). The methodology is widely used to determine the loss of ecosystem services when wetlands are converted to urban areas or are lost due to subsidence (Konarska et al. 2002; Tiner 2005; Chan et al. 2006; Craft et al. 2008; Di Sabatino et al. 2013).

Though prior research has evaluated hurricane effects on wetlands qualitatively in terms of storm surge, short-term effects, long-term effects and vegetation loss, these effects have not been quantified with regard to ecosystem services (Lugo 2008; Gornish and Miller 2010; Howard 2012; Murrow and Clark 2012; Ramsey et al. 2012). Previous analyses of hurricane impacts only give crude estimates of the degradation to wetlands; by quantifying effects in terms of ecosystem services we can provide a more comprehensive assessment of the location and extent of damage in a given wetland. Additionally, by quantifying the wetland degradation in terms of monetary ecosystem service loss, we can efficiently allocate environmental resources and, more importantly, reveal crucial economic information that might not previously have been considered in the restoration process (Troy and Wilson 2006; Liu et al. 2010). Wetlands in New Jersey are estimated to provide 10.6 billion dollars in ecosystem services per year, of which 9.4 billion dollars are from freshwater wetlands and 1.2 billion dollars are from saltwater wetlands (Costanza et al. 2006). The most valuable ecosystem services to humans are disturbance regulation and prevention, which serve to buffer storm surge and decrease damage to infrastructure (Costanza et al. 2006). We expect that severe degradation, e.g. marsh dieback and severe flooding, would impair a wetland's ability to buffer future storms.

Hurricane Sandy is an ideal storm for studying storm surge effects on wetlands, as its exceptional characteristics have been attributed to climate change (Halverson and Rabenhorst 2013). In this study we quantified the extent and severity of storm surge from Hurricane Sandy on the coastal wetlands of New Jersey by analyzing the degree of degradation and estimating the resulting loss of ecosystem services. Our analysis involved the following steps: 1) quantify the severity of the storm surge impact using an index that scores degradation and quantifies the extent of the impacts through Geographical Information System (GIS) mapping and computation of areal degradation, 2) assess the influence of salinity and vegetation type on the susceptibility of a wetland to hurricane degradation 3) assess the pattern of impacts across New Jersey using interpolation in GIS, and 4) quantify the effects in terms of ecosystem service loss.

Methods

The study area ranged from Hackensack to Cape May (261.84 km) along the eastern coast of New Jersey where storm surge intersected coastal wetlands (Fig. 1). The study area extended 400 m to 19.5 km inland. The total area analyzed was 7900 km^2.

Quantifying Severity and Extent of Effects

A map of the wetlands affected by Hurricane Sandy was created through an intersection of storm surge (NOAA 2012), wetland polygons (NJDEP 1986) and pre- and post-Sandy aerial photos (NJGIN 2012; FEMA 2012, respectively) in ArcGIS 10.1 (ESRI, Redlands, CA, USA). Wetland delineation and classification was done by the New Jersey Department of Environmental Protection as per Cowardin et al. (1979). We assigned metrics to each wetland based on visible degradation present in the post-Sandy photos using the 60–40 rule, which requires at least 60 % of a polygon to contain a certain degradation type (Bolstad 2005). The metrics assessed were: minimal flooding and minimal natural debris, forms of low degradation; moderate flooding, moderate natural debris and minimal artificial debris, forms of moderate degradation; and extreme flooding, moderate-severe artificial debris, severe natural debris, and marsh dieback (distinct brown patches), forms of severe degradation. During attribution we characterized minimal flooding as channel and pond expansion, moderate flooding as channel and pond expansion and creation, and severe flooding as scouring, submerged wetlands, as well as channel and pond expansion and creation (Ramsey et al. 2012). Natural debris (e.g. accumulation of wrack) and artificial debris (e.g. human infrastructure) are types of depositional events (Morton and Barras 2011). We characterized minimal natural debris as relatively small piles of wrack that were infrequent, moderate natural debris as piles of wrack that were frequent, and severe natural debris as relatively large piles of wrack within an individual wetland. Additionally, we characterized minimal artificial debris as the presence of any artificial debris and we characterized moderate artificial debris, as larger piles of artificial debris. We did not include a severe artificial debris category because we considered moderate amount of artificial debris to be a severe impact (Ramsey et al. 2012). Browned areas of dead vegetation and/or open sediment indicate marsh dieback (Ramsey et al. 2012). Photographic examples of marsh dieback, flooding, and artificial debris can be seen in Fig. 2. Note that

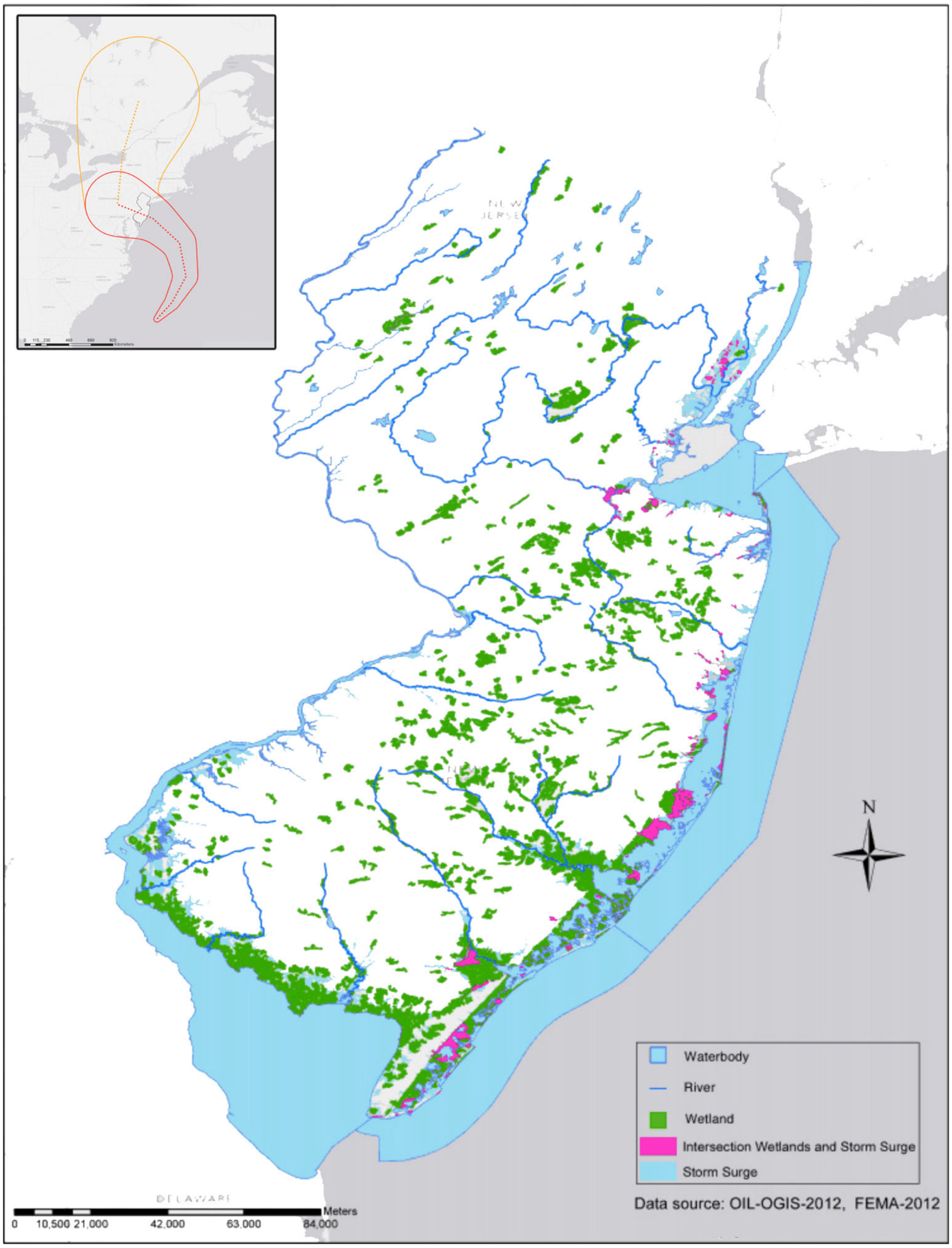


Fig. 1 Storm surge effects on coastal wetlands of New Jersey. Areas in pink are wetlands that experienced storm surge due to Hurricane Sandy and thus define our study area. Inset shows the path of Hurricane Sandy (black) through the northeast United States (OIL-OGIS 2012; FEMA 2012)

the most recent wetland polygon data for this area was from 1986. Wetlands that have changed in land use since then were dropped from the analysis. It is possible through this index that the same area be counted in multiple categories, however, this possibility is dramatically decreased through the use of the 60–40 rule. Any double counting that did occur would be negligible and would not affect the overall trends. Further, the canopy cover in forested wetlands made identification of degradation from aerial photos difficult. Nonetheless, we included these areas in the analysis.

A 3-tier degradation index, created by scoring and summing the nine ordinal metrics, was used to determine the extent and degree of impact in each of the affected wetlands (Table 1). Low degradation metrics were given a score of one, moderate degradation metrics, a score of two, and severe degradation metrics, a score of three. Thus, higher scores indicate greater impacts. After attribution of metrics and scoring for each wetland, we calculated a final score by summing the scores of all present metrics in a given wetland. For our degradation index, we deemed wetlands with a final calculated score of one or two as low impact, moderate impact wetlands scored three or four and severe impact wetlands scored five or more.

We used this degradation index to quantify the extent of impacts through GIS mapping and computation of areal degradation. Because each category of degradation affects

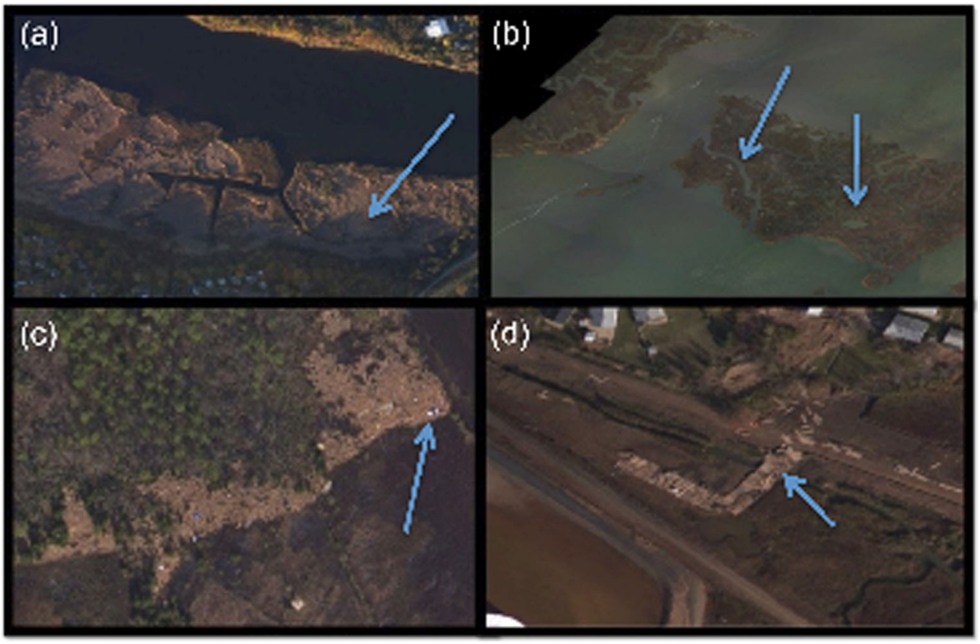


Fig. 2 Four forms of marsh degradation **a** Marsh dieback: vegetation death due to prolonged flooding has left open sediment subject to be permanently eroded away. **b** Moderate flooding: enlarged channels and ponds and the creation of ponds are typical characteristics of flooding in a marsh system that can degrade the existing wetland. **c**, **d** Artificial debris: damaged human infrastructure has been deposited onto wetlands via wind or subsiding floods

a wetland ecosystem and its respective ecosystem services differently, the location and extent of low, moderate and severe impacts were mapped individually. Wetlands can contain impacts of different categories; for example, a wetland could have moderate flooding (a moderate metric level) and marsh dieback (a severe metric level).

In addition to the degradation index described above, wetlands were categorized based on the time scale under which damage would likely be reversed. We defined long-term damage as degradation that will not be restored within 5 years (e.g., severe flooding, moderate to severe artificial debris, severe natural debris, and marsh dieback; Bakker et al. 1996). Short-term damage was defined as degradation remediated naturally or with human involvement such as short-term restoration (e.g., minimal flooding, minimal natural debris, moderate flooding, moderate natural debris, and minimal artificial debris; Bakker et al. 1996). Long-term and short-term damage are qualitative assessments of storm surge impacts.

Table 1 Metric scoring utilized in attribution of hurricane impacts (See Fig. 2 for aerial photography)

Low (score of one)	Moderate (score of two)	High (score of three)
Minimal flooding, Minimal natural debris	Moderate flooding, Moderate natural debris, Minimal artificial debris	Extreme flooding, Moderate-severe artificial debris, Severe natural debris, Marsh dieback (Distinct brown patches)

Assessing the Factors Influencing Susceptibility of a Wetland to Hurricane Degradation

We used our degradation index and wetland characteristics to assess the impact of vegetation type and salinity on wetland degradation. Since the degradation index creates scored data, the data were not normal and could not be normalized. We performed a negative binomial regression with an interaction and a least square means post-hoc test to assess the influence of salinity and vegetation type on the susceptibility of a wetland to hurricane degradation. Our discrete dependent variable was the degradation index score and our categorical independent variables were vegetation type (herbaceous versus woody; NJDEP 1986) and salinity (saltwater versus freshwater; NJDEP 1986).

Assessing Spatial Patterns

We used Moran's I, a method to measure spatial autocorrelation, to validate the presence of clustering within the wetland degradation index scores for use in the hot spot analysis (Mitchell 2005). We used hot spot analysis to identify patterns and levels of degradation for identified clusters. This type of analysis uses weighted features to create a map of statistically significant hot spots (high values) and cold spots (low values; Mitchell 2005). In this case, we based the weighted features in our hot spot analysis on the degradation index scores. Lastly, we used an Inverse Distance Weighted (IDW) interpolation based on the hot spot analysis to assess patterns in the storm surge impacts (McCoy 2004). Additionally, we performed a Moran's I and a hot spot analysis to determine if there was clustering of degradation severity across the study area.

Quantifying Effects with Ecosystem Services

It is unlikely that 100 % of the ecosystem services in any given wetland were lost as a result of hurricane degradation. To circumvent this problem, we created a stepped range of monetary ESV loss based on our degradation index. For each wetland polygon, we multiplied the area of the wetland by a value associated with its degradation category. The degradation categories have associated values as follows: minimal=0, low=0.25, moderate=0.50, and severe=0.75. For example, if a wetland received a degradation score of 4, then its area would be multiplied by 0.50. We then summed the total of area for each wetland type (Table 1) and multiplied it by the monetary ESV as determined by Costanza et al. (2006).

Results

Quantifying Severity and Extent of Effects

Hurricane Sandy generated extensive and severe impacts to New Jersey's coastal wetlands. We evaluated and attributed 2910 wetlands, representing 19 different wetland types along the coast of New Jersey (Table 2). In total we found 2743.19 km^2 of coastal wetlands had at least some form of degradation as a result of Hurricane Sandy. Moderate flooding (cumulatively covering an area of 1041.88 km^2) and marsh dieback (1010.41 km^2) were the most prevalent types of degradation in the study area while severe natural debris (91.80 km^2), moderate artificial debris (167.81 km^2), and minimal artificial debris (173.04 km^2) were the least common types (Fig. 3). Saline marshes (829.51 km^2, 69.2 %) and herbaceous wetlands (797.28 km^2, 45.5 %) were the most affected, respectively, in terms of area impacted (Table 2). However, when evaluating degradation in terms of percent of each type of wetland damaged, coastal wetlands were the most affected (7.97 km^2, 100 %) followed by saline marshes (829.51 km^2, 69.2 %), freshwater tidal marshes (85.44 km^2, 60.1 %), and vegetated dune communities (64.19 km^2, 59.9 %; Table 2). The hurricane more easily degraded wetland types with low standing vegetation, those found closer to the coast (e.g., herbaceous wetlands) than those with high standing vegetation, farther from the coast (e.g., forested wetlands).

Using our degradation index, we found that severe degradation was most prevalent (1409.19 km^2; 41.38 %), followed by moderate (1348.70 km^2; 39.60 %) and low degradation (647.53 km^2; 19.01 %), respectively. Saline marshes and herbaceous wetlands had the most severe damage (Table 2). In a visual examination of the three degradation index maps (Fig. 4), we found that low impacts were dominant in the northern range of our study area while moderate and severe impacts extended throughout the entire range but were predominately in the southern portion of the study area. However, the hot spot analysis indicated that there was no significant clustering for damage severity.

In our analysis of the time scale in which damage would likely be reversed, we found that 51.05 % of all degradation was long-term and 48.95 % was short-term. Long-term damage was most prevalent in saline marshes (441.87 km^2) and herbaceous wetlands (401.83 km^2; Table 2).

Assessing the Factors Influencing Susceptibility of a Wetland to Hurricane Degradation

A deviance ratio (value to degrees of freedom) of 0.90 indicated that our data fit the negative binomial distribution. According to the negative binomial regression, vegetation type and the interaction between vegetation type and salinity were statistically significant predictors of degradation index score ($X^2=92.85$, $P<0.0001$, $X^2=15.96$, $P<0.0001$, respectively).

Wetlands dominant in herbaceous vegetation, both freshwater and saltwater, had significantly high degradation index scores ($r=0.3723$, $P<0.0001$; $r=0.9853$, $P<0.0001$, respectively) while conversely, wetlands dominant in woody vegetation, regardless of salinity, had significantly low degradation scores ($r=-0.5562$, $P<0.0001$; $r=-1.1144$, $P<0.0001$, respectively). This indicates that herbaceous wetlands, regardless of salinity, have a significant positive relationship with the degradation index score, and woody wetlands, regardless of salinity, have a significant negative relationship with the degradation index score.

Assessing Spatial Patterns

In the visual examination of attributed degradation patterns, damage ran parallel to the hurricane's path, especially near the eye of the storm with clusters of severe impact near the Meadowlands and Cape May, New Jersey (Fig. 5). Further examination of hurricane impact distribution using Moran's I yielded a z-score of 4.38 ($P<0.00001$) which is well above 1.00, indicating substantial clustering. Our hot spot analysis and IDW interpolation of the hot spots predicted degradation along the length of the coast, however the area parallel with the hurricane's path was clearly shown to be the most impacted. We found three main clusters of damage: near the Meadowlands, Cape May, and Brigantine, New Jersey (Fig. 6). This was consistent with the visual examination from Fig. 5.

Quantifying Effects with Ecosystem Services

We calculated a total possible loss of $4,377,244,703 in ecosystem services due to the impacts of Hurricane Sandy's storm surge on New Jersey's coastal wetlands. Table 2 shows the monetary values associated with the loss of ecosystem

Table 2 A summary of impacts caused by Hurricane Sandy in New Jersey in each wetland type including: area impacted, percent impacted, area with long-term damage, and monetary ESV losses for minimal, low, moderate, and severe degradation. Wetland delineation and classification was done by the New Jersey Department of Environmental Protection as per Cowardin et al. (1979)

Wetland type	Total area (km^2)	Area impacted (km^2)	Percent impacted (%)	Low impact (km^2)	Moderate impact (km^2)	Severe impact (km^2)	Long-term degradation (km^2)	Minimal ESV loss (million USD)	Long ESV loss (milliion USD)	Moderate ESV loss (million USD)	Severe ESV loss (million USD)
Agricultural wetlands (modified)	40.03	13.09	33	0	0	13.09	13.09	0	0	34.62	46.16
Atlantic white cedar wetlands	191.24	18.89	10	5.72	7.9	5.27	5.27	2.67	7.38	7.39	9.85
Brush-dominant and Bog wetlands	3.58	1.7	48	0	0	1.7	1.7	0	0	4.5	6.01
Coastal wetlands	7.97	7.97	100	7.97	0	0	0	3.72	0	0	0
Coniferous scrub/shrub wetlands	91.98	26.32	29	0	26.32	0	0	0	46.38	0	0
Coniferous wooded wetlands	379.09	47.45	13	10.68	32.88	10.11	10.11	9.41	57.95	26.72	35.63
Deciduous scrub/shrub wetlands	853.12	250.42	29	56.13	132.44	128.8	146	49.46	233.43	340.43	453.91
Deciduous wooded wetlands	1309.5	154.32	12	26.76	73.21	68.76	68.76	23.58	129.04	181.78	242.37
Disturbed wetlands (modified)	296.58	138.96	47	28.18	96.46	55.14	47.46	24.83	170	145.78	194.37
Freshwater tidal wetlands	142.06	85.44	60	22.83	21.68	54.61	54.61	20.12	38.21	144.38	192.5
Herbaceous wetlands	1751.1	797.28	46	212.83	349.77	414.48	401.83	187.55	616.47	1096.72	1462.29
Managed wetlands (modified)	207.77	73.37	35	9.49	23.67	45.9	45.9	8.37	41.72	121.35	161.79
Mixed forested wetlands (coniferous dominant)	265.19	6.29	2	1.06	2.8	2.43	2.43	0.94	4.94	6.42	8.56
Mixed forested wetlands (deciduous dominant)	302	28.22	9	3.81	12.32	21.14	21.14	3.36	21.71	55.9	74.53
Mixed scrub/shrub (coniferous dominant)	136.16	27.92	21	7.8	7.78	23.04	22.65	6.88	13.72	60.91	81.21
Mixed scrub/shrub (deciduous dominant)	436.47	141.36	32	44.49	85.37	81.65	74.28	39.21	150.47	215.87	287.83
Saline marshes	1199.5	829.51	69	189.15	435.84	450.1	441.87	88.34	407.13	630.73	840.97
Vegetated dune communities	107.16	64.19	60	16.26	23.31	20.8	34.55	52.22	149.65	200.32	267.1
Wetlands rights-of-way (modified)	99.39	30.49	31	4.38	16.95	11.8	11.8	1.13	8.87	9.12	12.16
Total	7819.9	2743.19	–	647.53	1348.7	1409	1403.47	521.78	2096.94	3282.93	4377.24

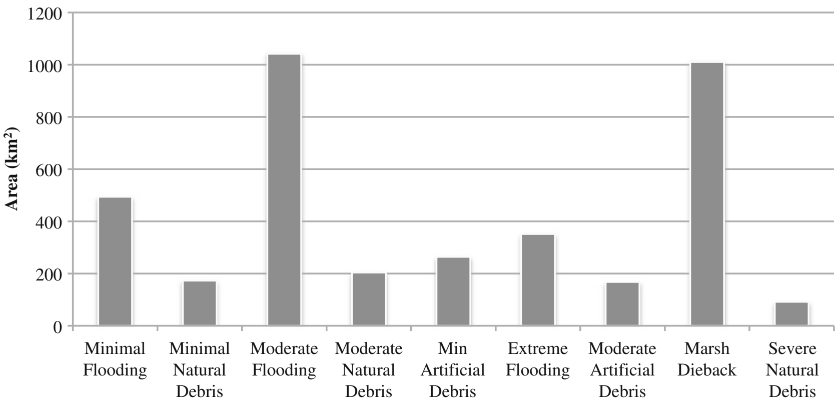
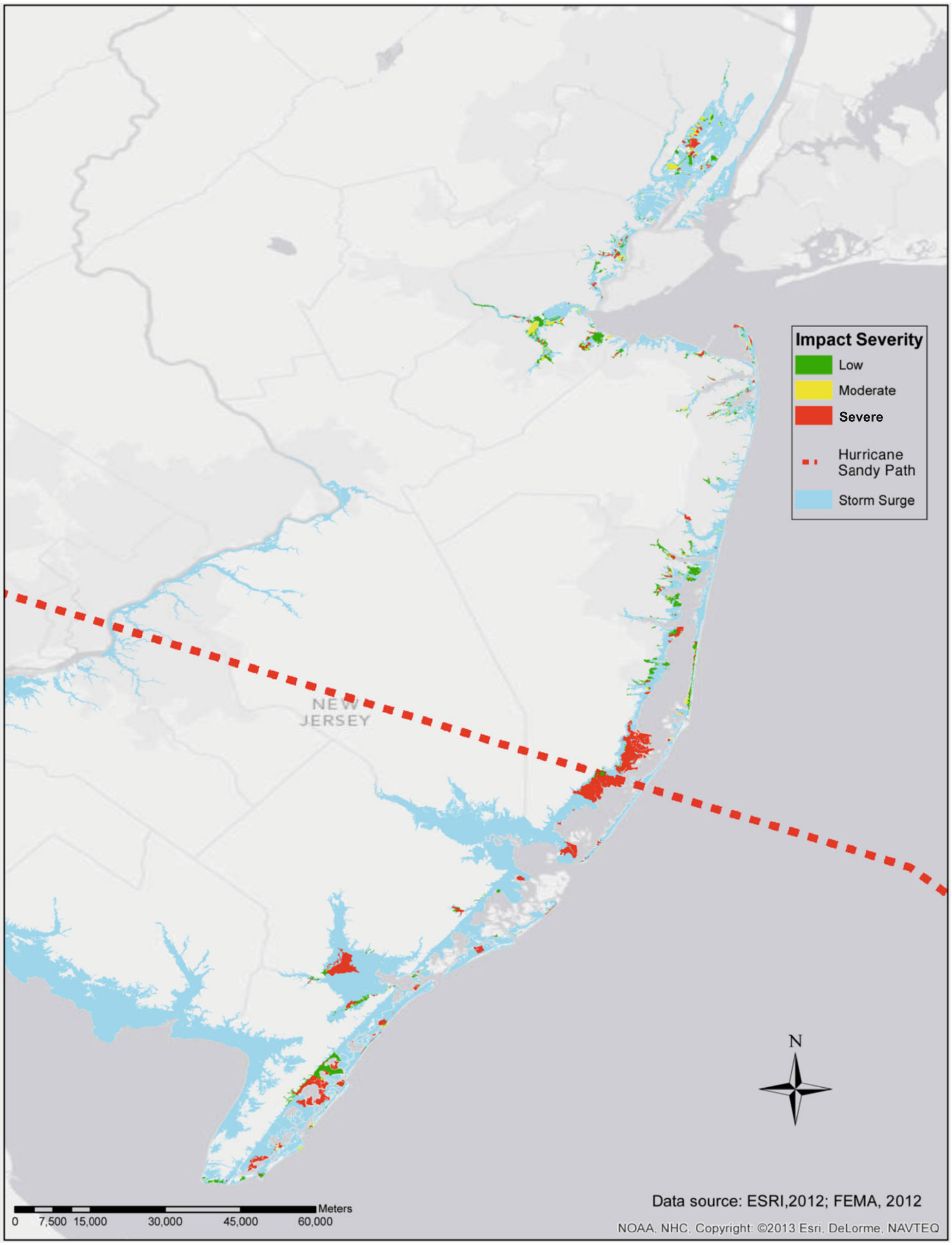


Fig. 3 Cumulative area of impacted wetlands sorted by degradation type



Data source: ESRI,2012; FEMA, 2012

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Fig. 4 Locations of low, moderate and severe degradation from Hurricane Sandy, October 2012, in coastal wetlands of New Jersey

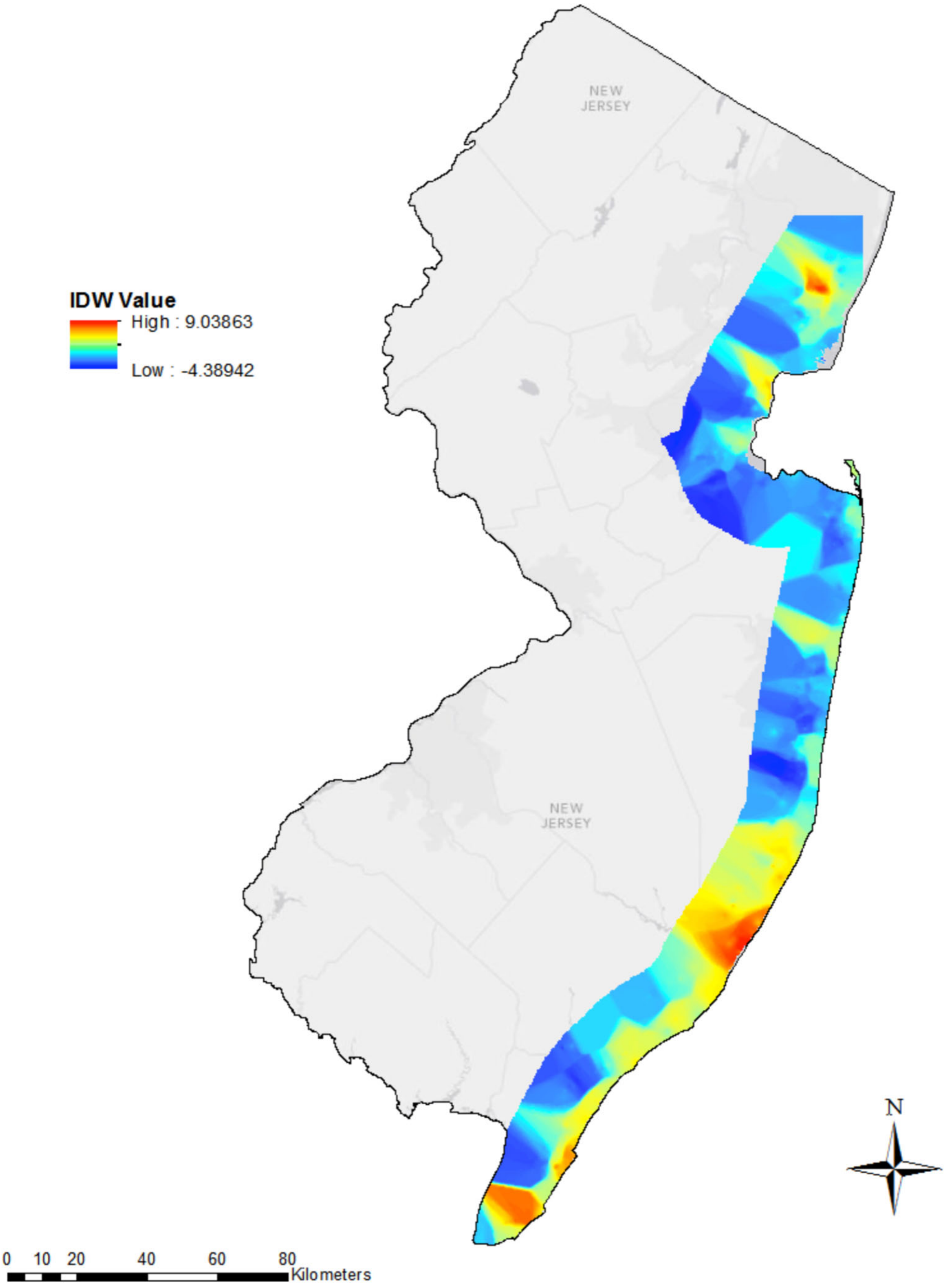

Fig. 5 Extent and severity of attributed wetland impacts by storm surge from Hurricane Sandy (Esri, 2012; FEMA 2012; NOAA 2012)

services due to Hurricane Sandy for each category in our ESV loss index. Wetlands that sustained minimal impact (>0–24.99 % degradation) lost up to $521,783,310, low impact (25–49.99 % degradation) lost $521,783,311 to $2,096,940,170, moderate impact (50–74.99 % degradation) lost $2,096,940,171 to $3,282,933,528, and severe impact (75–100 % degradation) lost $3,282,933,529 to $4,377,244,703 in ecosystem services, respectively (Table 2).

The majority of ecosystem service loss was found in herbaceous wetlands (33 %) and saline marshes (19 %) (Table 2). Monetary values of ecosystem service loss ranged from $187,553,945 to $1,462,294,372 and $88,342,931 to $840,967,761 for herbaceous wetlands and saline marshes, respectively (Table 2). Each of the rest of the wetland types sustained less than $500,000,000 in damages because less wetland degradation was sustained.

Discussion

It is not coincidental that the two largest sources of wetland degradation from Hurricane Sandy were moderate flooding due to storm surge and marsh dieback; flooding caused by surge is known to cause salt burning and subsequent marsh

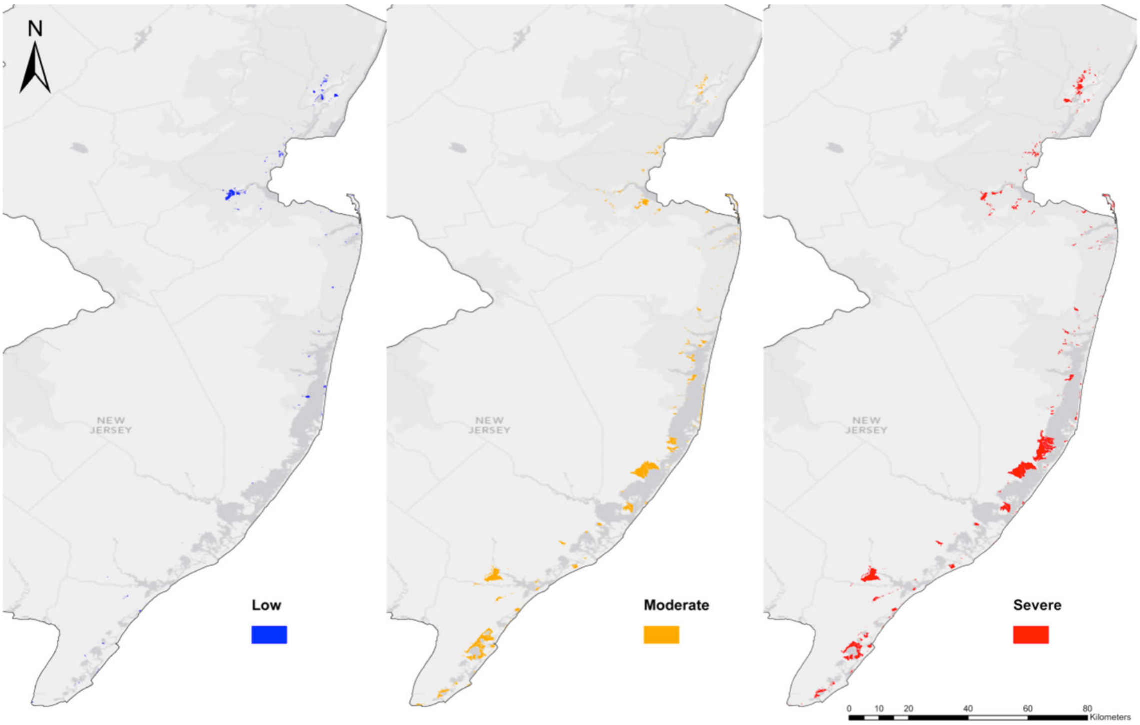

Fig. 6 Inverse distance weighted interpolation of hot spot analysis of wetland impacts. The high values (*red*) are areas modeled to have severe impacts while low values (*blue*) are areas modeled to have little to no impacts (Center for Remote Sensing and Spatial Analysis, 2012)

dieback (Ramsey et al. 2009). The sustained flood period during Hurricane Sandy exacerbated long-term marsh dieback through wetland erosion and vegetation loss (Ramsey et al. 2012). In fact, saline marshes are particularly sensitive to this correlative effect (Ramsey et al. 2012). During marsh dieback, plants die from increased salinity, allowing open sediment to be eroded away permanently and encouraging the marsh to retreat further inland (Morton and Barras 2011). Human alteration of wetlands, e.g. levees or development, also amplifies the effects of hurricanes, especially marsh dieback, by lengthening the flooding period with elevated salt levels (Neyland 2007; Ramsey et al. 2012). These effects appear to have combined in the wetland regions of our study area to create significant damage.

The relationships of degradation index score to dominant vegetation type and the interaction between the two are consistent with our predictions. Herbaceous plants provide fewer buffers from and increase the vulnerability of the damaging effects of storm surge compared to woody plants and are therefore more susceptible to degradation (Morton and Barras 2011). The large roots of woody plants cling to soil aggregates making it more difficult for erosion to take place. Additionally the large size of woody plants above the soil buffers against wind erosion, a function that herbaceous plants cannot provide (Gyssels et al. 2005).

Wetlands with herbaceous vegetation are more prone to ESV loss than those with woody vegetation. This is partially due to the structural integrity of woody vegetation relative to herbaceous vegetation and partially due to the proximity to the coast. Wetlands with woody vegetation tend to inhabit more inland areas where storm surge is already buffered to some degree by herbaceous wetlands (Burton et al. 2002). Therefore, herbaceous wetlands are not only providing ecosystem services through storm buffering for human infrastructure, albeit substantially less than those provided by woody wetlands, they are also providing buffers for more inland wetlands. This suggests that although herbaceous wetlands may be losing ESV through hurricane degradation, they are maintaining ESV in more inland wetlands through this buffering service.

Long-term damage presents a unique challenge for wetland managers seeking to restore impacted wetland areas. In New Jersey, 51.05 % of the damage from Hurricane Sandy was classified as long-term, with 88 % and 12 % of the damage being moderate and severe, respectively. Restoring wetlands is increasingly important to restoring ecosystem services, especially storm buffering, to neighboring communities with increasing severity and frequency of storms due to climate change. However, frequent and severe storms will likely continue to threaten New Jersey's coastline and restoration efforts, preventing managers from fully restoring these areas (Michener et al. 1997; Erwin 2009). For New Jersey wetlands that experienced long-term damage and loss of 50–75 % of their ecosystem services, restoration efforts must restore those ecosystem services before additional disturbances cause further decline in ecosystem value costing more money, time and effort.

The GIS analysis and IDW interpolation showed that damage occurred in two clusters: near Cape May and the Meadowlands and parallel to the storm's path and wind corridor. Damage paralleled Hurricane Sandy's path with the most severe degradation near where the eye of Hurricane Sandy made landfall (Fig. 5). This phenomenon is well documented in the literature (Barras 2007, 2009; Neyland 2007; ; Morton and Barras 2011). Since, the loss of ecosystem service values parallels this pattern, restoration efforts should be prioritized in the swath parallel to the hurricane's path in addition to the two clusters. The clusters found via interpolation represent areas where resources for wetland remediation and restoration would most efficiently restore ESV loss. Remediating and/or restoring large connected areas such as these sizable clusters would be helpful in returning proper ecological function to the wetlands. Fragmented wetlands, on the other hand, can be problematic for species health, especially those species that are threatened or endangered (Peintinger et al. 2003). This in turn can decrease the overall ecological function of the wetlands and the ecosystem services they provide (Ehrenfeld 2000).

Our ESV loss estimates account for a substantial portion (up to 50 %) of the ecosystem services provided by wetlands in New Jersey. This information in conjunction with the maps produced can be used to rapidly assess degradation after a storm. More importantly, these methods provide a quantitative value, which many other methods do not provide, that can be utilized in wetland management and restoration. ESVs can serve as a common language for the many parties (e.g., scientists, law makers, managers and private citizens) involved in wetland management. By incorporating ESVs into management decisions, stakeholders can prioritize regions for wetland restoration and remediation using a science-based process (Granek et al. 2010). Additionally, analyzing ESVs within GIS allows decision-makers to consider geographic location, wetland value and ecological interactions in a novel way when making management decisions.

Our ecosystem service estimates have limitations and should be considered as guidelines in remediation and restoration efforts. There are inherent errors in any mapping project, but we do believe that despite this, our methodology provides quantitative values that many other methods do not in evaluating storm degradation and allocating resources in wetland restoration. As these estimates are specific to the study region, it is important for those who use this methodology to remember that ESVs for land cover can vary by region and within a region (Woodward and Wui 2001). Future studies should use region-specific values as appropriate, as we relied on Costanza et al. (2014). The availability of such data at the national scale is one of the critical needs facing scientists right now so that future storm impact assessments can be conducted in other areas of the country. Additionally, ESVs reflect the economic status of the U.S.A. and would need to be altered based on the region's economy as appropriate (Zhang et al. 2013). Broad categories (e.g., beach, saltwater wetland, freshwater wetland, forest and grassland) as seen in some literature may limit the economic valuation possible by masking highly diverse wetland types (Costanza et al. 2006; Troy and Wilson 2006). The power in our site-specific methodology is that wetlands, especially highly diverse wetland types, are properly assessed and results are in a common language for all stakeholders in wetland restoration. Equally important, the ecosystem service estimates used in this study are cost-effective in both money and time as the protocol uses freely available GIS data and is rapidly applied.

Conclusion

When working within the ESV framework, decision makers should consider wetlands that have large ecosystem loss values per acre and wetland types that have low ecosystem loss values per acre, but have sustained large amounts of loss. Since, our ESV equation takes the area of a wetland into consideration in the calculation of ESV loss, large areas of common wetland types have large ESV loss values and are, therefore, important in any future restoration decisions. However, small fragments of important wetland types may also have large ESV loss values though they may not appear as important based on our calculation due to their small area. Herbaceous wetlands and saline marshes comprise a large portion of the study area and should be the top priority during Hurricane Sandy restoration plans, particularly those wetlands that experienced marsh dieback where Sandy's eye made landfall. The ESV analysis in conjunction with impact attribution and long-term damage identification all support the assertion that herbaceous wetlands and saline marshes experienced the most amount of damage. Our analyses indicate that the majority of severe damage is located near Brigantine, New Jersey, associated with high scores on the degradation index and high ESV loss values. However, we also need to consider rare wetland types such as vegetated dune communities, which have a smaller area but the largest ESV value per square kilometer since the ESV loss analysis may not reflect severe damage in these wetland types.

Wetland managers should give GIS analysis and ecosystem service values greater consideration in management plans and remediation efforts. Restoration and remediation efforts should include these types of analyses to more effectively allocate funding and energy. The methods presented here have considerable potential to identify the extent and severity of damage and potential loss of ESV in coastal wetlands as a result of storm surge. Our procedures use known principles and publicly available data. Further, our methods can be tailored for any region for which data exist. For these reasons, these methods have the potential to provide information on conditions in coastal wetlands following storms in other locations as well. Our degradation index, in conjunction with an ecosystem service loss estimate, can be used by wetland managers to effectively identify areas for remediation efforts and prioritize restoration attempts due to Hurricane degradation.

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