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# Impact of Hurricane Sandy on salt marshes of New jersey

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ABSTRACT

Hurricane Sandy, one of the largest Atlantic hurricanes on record, made landfall as an extratropical cyclone on the coast of New Jersey (29 October 2012) along a track almost perpendicular to the coast. Ten days later a northeaster caused heavy precipitation and elevated water levels along the coast. Two years of pre-storm monitoring and research in marshes of Barnegat Bay and the Delaware Estuary provided an opportunity to evaluate the impacts of Hurricane Sandy and the succeeding northeaster across the region. Peak water levels during Sandy ranged from 111 to 184 cm above the marsh surface in Barnegat Bay and 75–135 cm above the marsh surface in the Delaware Estuary. Despite widespread flooding and damage to coastal communities, the storm had modest and localized impacts on coastal marshes of New Jersey. Measurements made on the marsh platform illustrated localized responses to the storms including standing biomass removal, and changes in peak biomass the following summer. Marsh surface and elevation changes were variable within marshes and across the region. Localized elevation changes over the storm period were temporary and associated with subsurface processes. Over the long-term, there was no apparent impact of the 2012 storms, as elevations and regression slopes pre- and several months post-storm were not significant. Vegetation changes in the summer following the fall 2012 storms were also variable and localized within and among marshes. These results suggest that Hurricane Sandy and the succeeding northeaster did not have a widespread long-term impact on saline marshes in this region. Possible explanations are the dissipation of surge and wave energy from the barrier island in Barnegat Bay and the extreme water levels buffering the low-lying marsh surface from waves, winds, and currents, and carrying suspended loads past the short-statured marsh grasses to areas of taller vegetation and/or structure. These findings demonstrate that major storms that have substantial impacts on infrastructure and communities can have short-term localized effects on coastal marshes in the vicinity of the storm track.



## 1. Introduction

Hurricanes have the potential to cause abrupt and occasionally long-term changes to the hydrology, morphology and biological community of coastal marshes. However, recent studies call into question the relative importance of episodic large storms on important physical processes such as sediment deposition (Smith et al., 2015) and lateral erosion (Leonardi et al., 2016) over the long-term. These studies suggest that for coastal marshes, frequent and regular events (e.g., river flooding, tides, wind) have a greater influence on marsh morphology over the long-term than infrequent high energy storms. This is significant because episodic disturbances have been thought to represent important mechanisms for marshes to overcome sediment deficits and keep pace with sea-level rise (Goodbred and Hine, 1995; Roman et al., 1997). In addition to their temporal importance, the magnitude of hurricane effects on marshes is also determined by the spatial breadth of impact. The effects of storms on low-lying marshes are often localized and spatially variable depending on factors such as storm intensity, location relative to storm track, and geomorphology (Guntenspergen et al., 1995). Factors such as hurricane size, intensity, coastline elevation and angle to which the hurricane makes landfall all contribute to wetland impacts (Resio and Westerink, 2008). Erosion of marsh edges and surfaces may depend on the coupling between water and wind, specifically water depths during time periods of maximum wind stress (Morton and Barras, 2011). Landscape features such as barrier islands, which may be a source of sediment for back-barrier marshes (Donnelly et al., 2001), can reduce storm impacts on mainland marshes by reducing wave energy and wave heights (Stone and McBride, 1998; Dietrich et al., 2011).

Nonetheless, localized, and occasionally regional, effects of

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storms can be impressive. Immediate effects include temporary increases in water levels associated with storm surge, storm tides, and heightened wave activity, which can have direct impacts such as the uprooting and removal of vegetation (Chabreck and Palmisano, 1973; Guntenspergen et al., 1995), deposition of sediments (Cahoon et al., 1995a) and organic debris (Mckee and Cherry, 2009), and scour and erosion (Howes et al., 2010). Physical impacts can include folding, tearing, and compression of the marsh (Guntenspergen et al., 1995), altering local flooding dynamics and elevation. Ponds formed by storm-induced erosion can remain part of the marsh landscape for decades or longer (Morton and Barras, 2011). While evidence of storms such as sediment deposits can be found 214 km from the storm track (Tweel and Turner, 2012), they are more often found in the vicinity of inlets or overwash fans (Roman et al., 1997; Donnelly et al., 2004). Individual storms can deposit sediments three orders of magnitude higher than pre-storm deposition (Cahoon et al., 1995a) and 9 cm thick (Nyman et al., 1995). Hurricane Katrina (29 August 2005) was implicated in leaving behind a 50-cm thick coarse-grained sand layer in a marsh along Bay Champagne in south Louisiana (Naquin et al., 2014). Locally, vegetation structure can influence spatial variation in storm deposition. During Hurricane Andrew in 1992, sediment deposition in stands of *Juncus roemerianus* was almost two times greater than in stands of *Spartina alterniflora* associated with a greater stem density (Nyman et al., 1995). In turn, sediments and organic material deposited from storms can serve as a source of nutrients (Nyman et al., 1995) and provide an escape from high sulfide concentrations, increasing plant productivity (Mckee and Cherry, 2009; Baustian and Mendelssohn, 2015). Sedimentation from hurricanes can often be greater than long-term annual accretion (Nyman et al., 1995; Baumann et al., 1984) and can lead to longer-term elevation changes. Hurricane Katrina deposited 3–8 cm of organic sediment in two subsiding salt marshes in the Mississippi River delta, Louisiana, and this deposition aided in a net elevation gain of 0.7–1.7 cm when recorded two years after the event (Mckee and Cherry, 2009). However, much of what we know about the effect of hurricanes on coastal wetlands is from the rapidly subsiding deltaic marshes of the northern Gulf of Mexico (Baumann et al., 1984; Connor et al., 1989; Reed, 1988; Day et al., 1995; Cahoon, 2006), where large storm events are relatively frequent. Less is known about the effects of hurricane strikes on marshes along the Atlantic coast, particularly in the mid-Atlantic where return periods for hurricanes of $\geq$64 kt range from 15 to 20 years (http://www.nhc.noaa.gov/climo/#returns). Understanding the impacts of hurricanes on coastal systems along the Atlantic is important as the frequency of the strongest hurricanes is predicted to increase (Bender et al., 2010).

Hurricane Sandy, one of the largest Atlantic hurricanes on record, made landfall as an extratropical cyclone near Brigantine, New Jersey at 2330 h on 29 October 2012. Sandy originated as a tropical wave along the west coast of Africa on 11 October (Blake et al., 2013). By late 21 October the circulation of the low pressure system was well defined south of Jamaica. The cyclone intensified as it passed over Jamaica and became a major hurricane with wind gusts of 100 kt prior to landfall in Cuba. As Sandy accelerated northward, it encountered colder waters and a high pressure pattern over the North Atlantic, which weakened the storm and prevented its passage out to sea, respectively (Blake et al., 2013). Storm-force winds extended over 900 km from the center, affecting Atlantic coast states from Florida to Maine (FEMA, 2013). The extratropical cyclone made landfall on the New Jersey coast with an estimated intensity of 70 kt. Wind gusts approached 80 mph (Sullivan and Uccellini, 2012) and just south of landfall at Atlantic City, storm surge peaked at 1.77 m (Blake et al., 2013). Coastal inundation and precipitation associated with the storm averaged 1.16 m and 15.60 cm, respectively (Blake et al., 2013). Hurricane Sandy's trajectory followed an almost unprecedented track, with an impact angle almost perpendicular to the shoreline. The likelihood of a hurricane following a similar track was estimated at 1 in every 714 years (Hall and Sobel, 2013) and storm surges of Sandy's magnitude in this region occur on average every 400–800 years (Lin et al., 2012; Aerts et al., 2013). Ten days after Hurricane Sandy made landfall on 8 November 2012, a northeaster delivered rain, snow, and gusty winds along the coast of New Jersey and neighboring states.

Pre-hurricane monitoring and research in coastal marshes of Barnegat Bay and the Delaware Estuary, New Jersey provided the opportunity to evaluate the impact of Hurricane Sandy and the northeaster that followed on marsh accretion, elevation change, and vegetation. In Barnegat Bay, Hurricane Sandy caused geomorphic changes to the barrier island including widespread shoreline retreat (46% of shoreline), which averaged 12 m and the creation of two breaches in the northern section near Mantoloking (Miselis et al., 2015). Marshes on the barrier island and mainland of Barnegat Bay, as well as marshes that lay south-west of the storm track on the New Jersey bay shore of the Delaware Estuary were the focus of this study. Accretion, elevation change and vegetation data collected since 2011 allowed an opportunity to examine the effect of the fall 2012 storms. Water level data were collected prior to and over the storm period. For this evaluation, we also collected post-storm soil bulk density and percent sand content to characterize potential storm deposition.

## 2. Study areas

The effects of Hurricane Sandy and the succeeding northeaster on salt marsh accretion, elevation change, and vegetation were examined in six marshes along the mid-Atlantic coast in Barnegat Bay and the Delaware Estuary. Marsh sites were within 35 km of the Atlantic Ocean and ranged from 26 to 72 km from the storm track. The eye of Hurricane Sandy tracked southwest of Barnegat Bay marshes and northeast of the Delaware Bay marshes (Fig. 1). The six marshes included in this study were part of a larger regional assessment of wetland integrity, the Mid-Atlantic Coastal Wetland Assessment (MACWA).

Geomorphic settings of the marsh study sites varied across the region (Fig. 1). Two back-bay and one barrier island marsh in Barnegat Bay and three marshes along tidal tributaries varying in size in Delaware Bay were included in this study (Fig. 2). Barnegat Bay is a shallow coastal lagoon (depth averaging ~2 m) extending 62.7 km along the coast of New Jersey. The estuary is connected to the Atlantic Ocean via Barnegat and Little Egg Inlets and experiences a relatively small tidal amplitude ranging from 20 to 50 cm depending on location in the bay (Defne and Ganju, 2014). Mean salinity in the bay ranges from 18 to 25 with lowest salinities in the northern part of the bay farther from the inlets and near Toms River (Kennish, 2001). Reedy Creek marsh (RC) is along a back-barrier tidal creek in the northern part of Barnegat Bay south of the Mantoloking Bridge. RC was directly across the bay from where Sandy created a new inlet in the barrier island, which was manually filled in within a week of the hurricane. The barrier island marsh in Island Beach State Park (IBSP) is located mid-bay on Barnegat Bay Island approximately 4 km north of Barnegat Inlet. IBSP marsh is bordered to the east by scrub forest and a road, however, it may be subject to overwash during large storms from sandy dunes approximately 400 m to the east. Channel Creek (CC) marsh was located in the southern part of the bay on a small (~0.8 $km^2$) peninsula just north of Dinner Point Creek. The Delaware Estuary, by comparison, is a large coastal plain estuary (~17,680 $km^2$) open to the coastal ocean and experiences a tidal amplitude of ~1.5 m

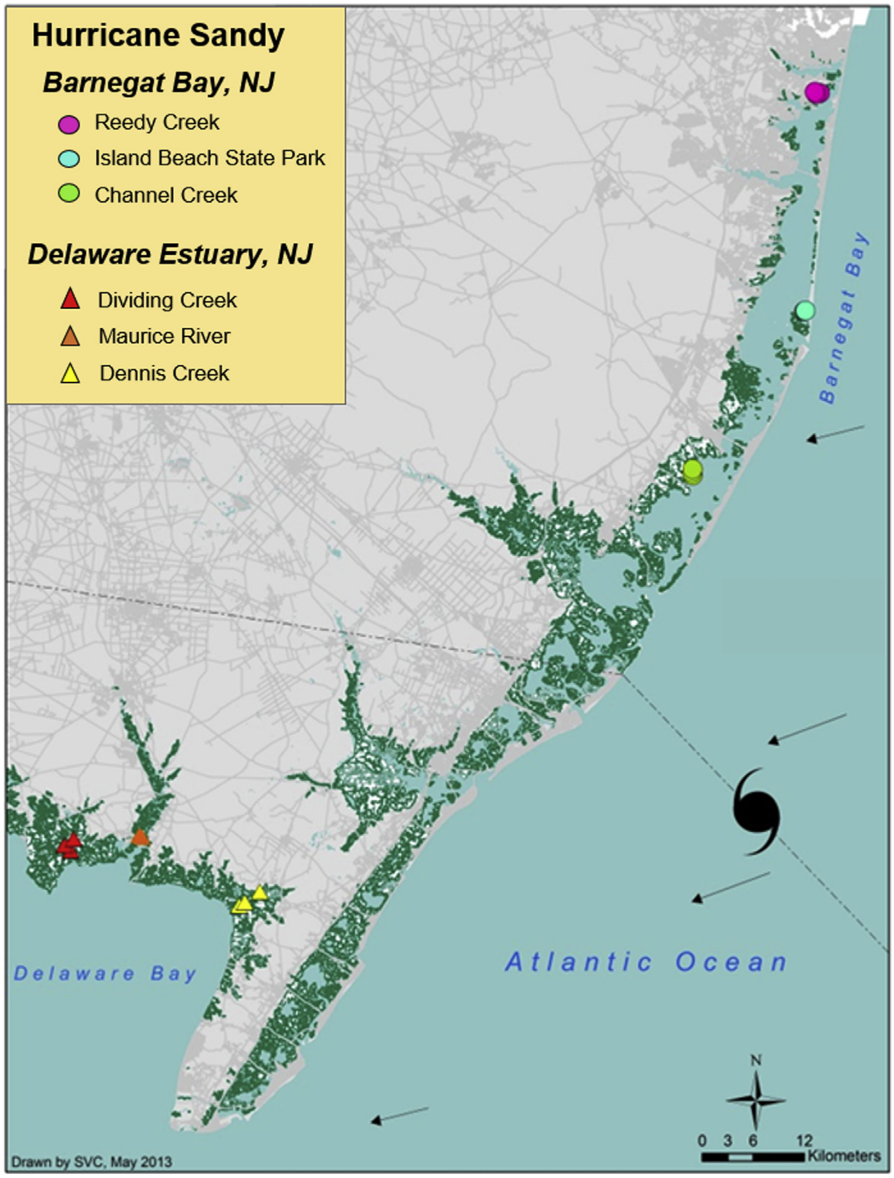


**Fig. 1.** Marsh study sites in Barnegat Bay and the Delaware Estuary, New Jersey. The track of Hurricane Sandy in October 2012 is illustrated by the dotted black line and the prevailing wind direction prior to landfall is represented by arrows.

near study locations, which is modulated by estuary and tidal channel geometry. The three marshes in the Delaware Estuary were located in the mesohaline portion of the estuary along tidal channels on the New Jersey bay-shore. Dividing Creek (DV) marsh was the farthest upstream of the study sites. Located in Downe, New Jersey, DV meanders for approximately 21 km from its headwaters to its confluence with the Delaware Estuary (PDE, 2014). The study area in DV was along a 1.5 km stretch of marsh along the meandering tidal channel approximately 1 km from the confluence with the Delaware Estuary. The Maurice River marsh (MR) is located approximately 3 km from the mouth of the Maurice River, the largest tributary included in this study. The Maurice River watershed area is 1000 km$^2$ with the main channel extending approximately 80 km northeast through Salem County. Dennis Creek marsh (DN) is along a 14 km tributary in Cape May County, NJ and is the closest to the mouth of the Delaware Estuary (Fig. 1). The study area at DN occurs between 1 and 3 km from the mouth of the tributary.

## 3. Methods

Marshes were dominated by *Spartina alterniflora*, and measurements were focused in the marsh interior approximately 15 m from a tidal channel. The study design in each marsh was based upon the establishment of three permanent surface elevation tables, each paired with three feldspar marker horizon plots (SET-MH; Cahoon and Turner, 1989; Cahoon et al., 2002). SET-MHs were established between the summer of 2011 and spring of 2012. In each marsh, the three SET-MHs were established at relative locations of “near”, “mid”-, and “far” along a transect perpendicular to the estuary (Fig. 2). Transect lengths ranged from 270 to 2970 m long with distances between SETs varying depending on size and configuration of the marsh. In marshes with prominent tidal channels, SET-MHs were placed on alternate sides of the tidal channel. One exception is MR where land ownership limited site selection to a 0.45 km$^2$ point bar along a meander in the tidal river where SET-MHs were placed along a perpendicular transect

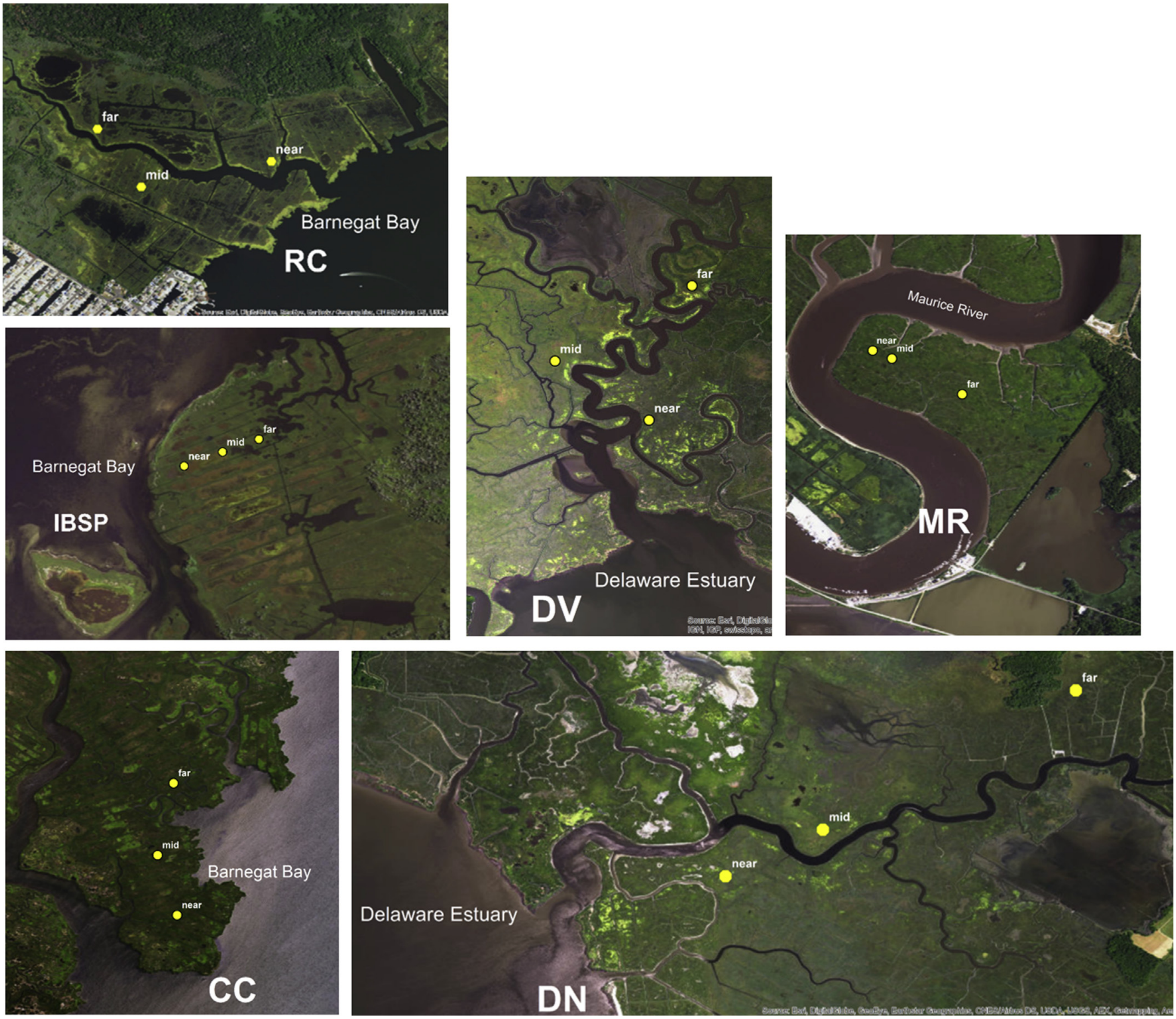


**Fig. 2.** Aerial images of salt marsh study locations in Barnegat Bay (left) and the Delaware Estuary (right). Yellow symbols represent SET-MH locations at near, mid, and far distances from the estuary and/or major water body. Image sources: World Imagery (Esri, Digital Globe, GeoEye, i-cubed, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relative to the river bend. Water level recorders and vegetation plots were established in each marsh in close proximity to SET-MHs at the near and far ends of transects relative to the estuary.

### 3.1. Water level

Two water level recorders (In-Situ 5000 vented) were installed in each of the six marshes from August 2012 to October 2013. Probes were placed approximately 10 m from SETs near and far from the estuary in each marsh. Probes were installed in slotted wells to a depth of 70 cm. The well cap containing the vented portion of the cable was 50 cm above the marsh surface at the bottom and 80 cm above the marsh surface at the top. Water level was recorded every 15 min. During Hurricane Sandy water levels rose above the top of the probe and thus water levels above 80 cm were not recorded. To extrapolate water level during Hurricane Sandy, relationships between water levels measured in the marsh and local tide gauge water levels were determined. In Barnegat Bay, USGS tide gauge 01,408,167 at Mantoloking Bridge was used for extrapolation of water levels in RC, USGS 01,409,125 gauge at Barnegat Inlet was used to extrapolate water levels in IBSP, and USGS 01,409,335 at Little Egg Inlet was used for CC. In the Delaware Estuary, USGS tide gauge 01,412,150 at Maurice River at Bivalve was used for DV and MR and USGS 01,411,435 at Sluice Creek was used for DN. Equations used to extrapolate high water levels during Hurricane Sandy were based on significant relationships between MHW across a two month period prior to the storm. Three survey points were collected on the marsh surface around each well using a Leica G-14 (see *Elevation* section below) and water level data were converted to NAVD88. The pressure sensors on two of the twelve probes (RC near and MR far) were faulty and therefore, these data were excluded.

### 3.2. Post-hurricane soil properties

Following the passage of Hurricane Sandy, soil bulk density and sand and silt/clay fraction were determined for five cores from each of the six marshes. Cores were collected at five random locations between each of the SET-MH locations using a Russian peat corer (5-cm diameter). Based on our observation that there was no evidence of storm deposition, cores were sectioned into 2-cm depth intervals from the surface to 4 cm depth in the field. Soil bulk density was calculated using mass/volume following sediment drying at 60 °C to a constant weight. Fractions of sand versus silt/clay were distinguished using size fractionation through manual sieving (Folk, 1968). Sediment retained on 4ϕ sieve (0.0625 mm) was considered sand with smaller particles representing silt and clay fractions.

### 3.3. Surface accretion

Feldspar plots were placed adjacent to SETs during the initial measurement ($T_0$) to be able to distinguish surface processes (e.g., deposition and surface root growth) from subsurface processes (e.g., swelling, compaction; Cahoon et al., 1995b). Accretion of material on the soil surface due to Hurricane Sandy was determined by measuring the difference in the vertical increments of accumulation above feldspar marker horizons before (<1 week) and after (5 marshes < 1 month and IBSP marsh slightly > 1 month) the hurricane. Short-term accretion rates were determined by collecting one square plug in each of the three plot areas adjacent to each of three SETs per marsh and measuring the distance from the top of the feldspar to the marsh surface on three of four sides. Changes in accretion before and after the storm were compared to the longer-term trend based on measurements collected two times per year for approximately 4 years. Loss on ignition was determined for material accumulated above marker horizon following 4 h in a furnace at 500 °C.

### 3.4. Elevation change

Deep benchmarks were driven vertically into the marsh to the point of refusal (13–27 m depth). Changes in marsh surface elevation were measured using a portable arm and a series of fiberglass rods, which were placed at the marsh surface in the same location in four cardinal directions around the benchmark during each sampling event. The height of each rod above the arm was measured to the nearest millimeter on successive sampling events. SET data were collected two times per year and additionally, before and after Hurricane Sandy (Table 1).

### 3.5. Elevation survey

In order to evaluate potential changes in marsh elevation beyond plot-level SET measurements, elevation surveys were conducted before and after the fall 2012 storms. During mid-summer (July/August 2012 and 2013) marshes were surveyed along permanent transects using satellite data gathered by GPS (Leica GS-14). Depending on marsh configuration and size, three or nine transects were surveyed. In marshes with tidal channels, nine transects were surveyed from the channel edge to the marsh interior with three at each near, mid, and far locations from the bay. In marshes without a prominent tidal creek (IBSP) and at MR three transects were surveyed from the marsh edge to the interior. Minimum transect distances were 100 m. A minimum of 15 points were collected per transect with a minimum of 52 points collected per marsh. Orthometric heights were derived in WGS84 NAD_83 (2011) Geoid 12A. Horizontal and vertical accuracies for the kinematic surveys were up to 1 and 2 cm, respectively. Point recapture errors greater than a 5 cm horizontal distance were removed from the analysis based on the survey rod foot diameter of 6.5 cm. Additional outliers were removed according to the equation: $\frac{Y_1 - \overline{Y}}{s}$, where $Y_1$ is the potential outlier, $\overline{Y}$ is the annual elevation mean of each marsh, and $s$ is the associated standard deviation (Sokal and Rohlf, 1995). DV was not surveyed in 2011 and CC was not surveyed in 2012.

### 3.6. Vegetation characteristics

Vegetation characteristics were determined in July and August in the two years prior to (2011 and 2012) and the summer following (2013) Hurricane Sandy for two marshes in each estuary. Species composition, aboveground biomass, stem density, and shoot height were determined in six 0.25 $m^2$ plots. Three replicate plots were located near the estuary (~10 m from SET 1) and three were located farther from the estuary (~10 m from SET 3). Vegetation plots at each SET were approximately 2 m apart. Aboveground biomass was harvested at the soil surface. Stem density was determined by counting the number of live stems of each species. Average height of each species was determined by counting the number of live stems in 10-cm height intervals (i.e., 0–10, 10–20, 20–30 cm, etc.). The midpoint of each height interval was multiplied by the number of stems for each species to calculate an average shoot height. Biomass was determined by drying live and dead plant material of each species in a drying oven at 60 °C to a constant weight.

### 3.7. Data analysis

To assess the impact of Hurricane Sandy on vegetation, accretion and elevation change, we used repeated measures analyses of variance (ANOVA) models. Impacts due to Hurricane Sandy were

**Table 1**
Data collection dates before and after Hurricane Sandy made landfall on the coast of New Jersey on October 29, 2012 in salt marshes of Barnegat Bay and Delaware Estuary, New Jersey.

| Estuary | Site | Parameter | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Vegetation characteristics | | | Russian peat cores | Elevation (NAVD88) | | Accretion and elevation change | |
| | | Before storm | | After storm | After storm only | Before storm | After storm | Before storm | After storm |
| Barnegat | RC | 7/26/2011 | 08/30/12 | 08/05/13 | 04/26/13 | 08/30/12 | 07/26/13 | 10/24/12 | 11/16/12 |
| | IBSP | 7/28/2011 | 08/08/12 | 08/07/13 | 06/21/13 | 08/28/12 | 08/15/13 | 10/24/12 | 12/03/12 |
| | CC | | 08/09/12 | 08/06/13 | 04/08/13 | | 08/06/13 | 10/22/12 | 12/03/12 |
| Delaware | DV | | | 07/09/13 | 06/25/13 | 08/17/12 | 08/19/13 | 10/23/12 | 11/14/12 |
| | MR | 6/28/2011 | 07/02/12 | 07/08/13 | 05/14/13 | 09/07/12 | 09/11/13 | 10/25/12 | 11/14/12 |
| | DN | 7/14/2011 | 07/16/12 | 07/25/13 | 06/26/13 | 09/10/12 | 07/25/13 | 10/23/12 | 11/15/12 |

considered differences in post-hurricane variables as compared to the two years prior. For accretion and elevation change data, annual rates of change for the two years prior to Hurricane Sandy were obtained using Type II regression analyses. One-way repeated measures analysis was used to test whether the rate of change (mm/d) differed among all sampling points including those immediately after the storm. To account for seasonal and time-dependent variability, daily rate of change in accretion and elevation change was calculated for each measurement interval, rather than using linear regression over the time series. Rates of change over the storm period were then compared with daily rates calculated over each measurement interval to test whether changes over the storm period fell outside of any previously measured changes. Tukey tests were used for post hoc multiple comparisons among sampling intervals. To test the longer-term (1 year) effect of Hurricane Sandy on accretion and elevation change, we compared the slopes of the regression lines obtained in the two years prior to the storm to the slopes obtained in the year following the storm ($n = 3$ per marsh). Stem density and shoot height were log-transformed to improve normality. Post-hoc comparisons were made using Tukey HSD test.

## 4. Results

### 4.1. Water level

In the two months prior to Hurricane Sandy, mean high water (MHW) above the marsh surface ranged from 1 to 19 cm across marshes (Table 2). Hurricane Sandy caused water levels to rise 4 to 75 times higher than that during MHW, depending on marsh location and elevation (Table 2; Fig. 3). Maximum water levels during Sandy were greatest at RC, peaking at 184 cm above the marsh surface. The two back-bay marshes, RC and CC, experienced higher maximum water levels than the barrier island marsh, IBSP. Maximum water level in the Delaware Estuary during Sandy was greater in marshes closer to the estuary mouth (DN) than farther up-estuary (DV), and in areas closer to the mouth of tidal channels (near) than farther up-channel (far). Water levels remained above MHW continuously for 30–53 h in Barnegat Bay marshes and intermittently following natural tidal frequencies for 40–59 h in the Delaware Estuary before returning to pre-storm tidal heights (Fig. 3). Tidal heights in Barnegat Bay remained elevated for several days after the storm. The northeaster that followed 10 days after the passage of Hurricane Sandy caused maximum water levels 32–125 cm lower than those during Sandy (Table 2; Fig. 3). Water level heights during the northeaster were generally similar across marshes; however, the duration of water level above MHW was over three times longer in Barnegat Bay than in the Delaware Estuary.

### 4.2. Post-hurricane soil analysis

Information on pre-storm bulk density and sand content of surface sediments of marsh study sites was lacking, and therefore the goal of collecting post-storm soil data was to determine whether there was a distinct surface layer of high bulk density and/or high sand content, which may serve as an indicator of storm deposits. Surface soils (0–2 cm) had similar bulk densities and sand contents to subsurface soils (2–4 cm; Table 3), and could not be visually distinguished from subsurface layers based on color, texture, or the lack of roots and rhizomes. Overall, there were no observable signs of storm-related deposition at our study locations.

### 4.3. Surface accretion

Annual rate of surface accretion prior to the Fall 2012 storms was positive for three of five marshes, ranging from an average of 5.4–17.0 mm/yr (Table 4a). Over the storm period, surface accretion/erosion across the marsh (near, mid- and far locations) fell within the range of variability measured prior to the storm ($p > 0.05$; Table 4a, Figs. 4 and 5). Repeated measures analysis indicated that daily rates of change across near, mid- and far locations did not vary significantly among any of the measurement intervals including those over the storm period ($p > 0.05$, $n = 3$).

**Table 2**
Water level characteristics in marshes of two mid-Atlantic estuaries before and during Hurricane Sandy and a northeaster in 2012. Mean high water data were calculated using the mean of high tides for approximately three months preceding Sandy.

| Estuary | Site | Location | Mean high water (cm) pre-storm | | Hurricane sandy | | | | Northeaster | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Date/time | Max water depth (cm) | | Duration above MHW (hrs) | Date/time | Max water depth (cm) | | Duration above MHW (hrs) |
| | | | Relative to marsh surface | Relative to NAVD88 | | Relative to marsh surface | Relative to NAVD88 | | | Relative to marsh surface | Relative to NAVD88 | |
| Barnegat | RC | far | 11 ± 1 | 22 ± 1 | 10/30 2:59 | 184 | 196 | 30 | 11/8 11:59 | 61 | 73 | 16 |
| | IBSP | near | 12 ± 1 | 28 ± 1 | 10/29 17:42 | 112 | 128 | 43 | 11/8 3:12 | 50 | 66 | 17 |
| | | far | 10 ± 1 | 23 ± 1 | 10/29 21:58 | 111 | 124 | 41 | 11/8 7:13 | 57 | 70 | 19 |
| | CC | near | 3 ± 1 | 46 ± 1 | 10/29 19:23 | 151 | 193 | 41 | 11/8 2:38 | 32 | 74 | 21 |
| | | far | 5 ± 1 | 34 ± 1 | 10/29 19:22 | 152 | 193 | 53 | 11/8 7:22 | 40 | 81 | 18 |
| Delaware | DV | near | 1 ± 1 | 93 ± 1 | 10/29 22:19 | 75 | 170 | 59[a] | 11/8 4:12 | 9 | 104 | 4 |
| | | far | 16 ± 1 | 62 ± 1 | 10/29 23:28 | 60 | 115 | 40[a] | 11/8 5:43 | 28 | 83 | 5 |
| | MR | near | 18 ± 1 | 77 ± 1 | 10/29 22:03 | 107 | 165 | 49[a] | 11/8 5:18 | 54 | 112 | 5 |
| | DN | near | 18 ± 1 | 88 ± 1 | 10/29 22:44 | 135 | 205 | 51[a] | 11/8 3:59 | 60 | 130 | 3 |
| | | far | 19 ± 1 | 79 ± 1 | 10/29 22:25 | 122 | 182 | 53[a] | 11/8 5:55 | 60 | 120 | 4 |

[a] Non-continuous with tidal oscillations.

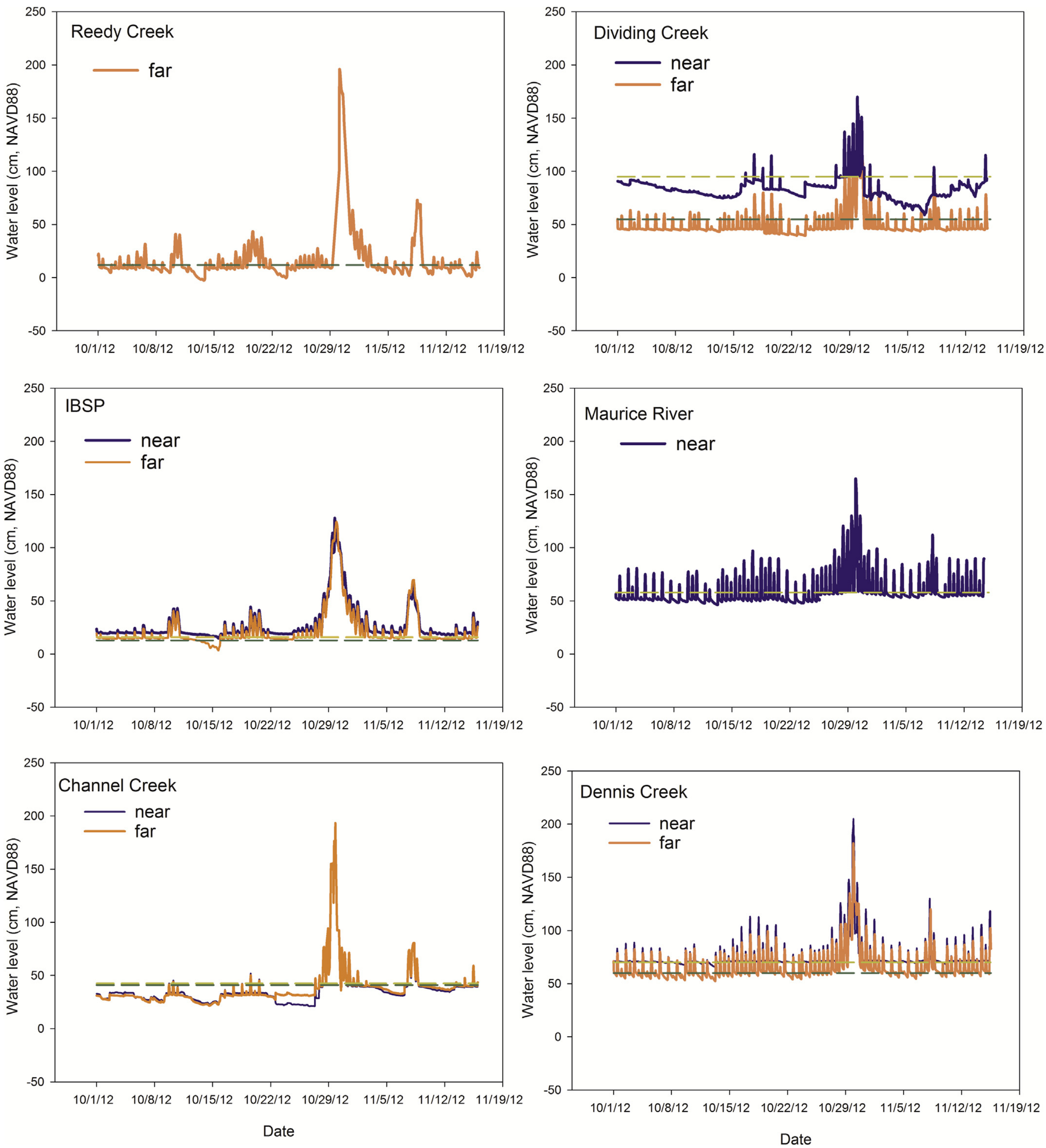


**Fig. 3.** Water levels relative to NAVD88 in marshes of two mid-Atlantic estuaries before and during Hurricane Sandy and a Northeaster in 2012. Horizontal lines represent the marsh surface elevation (gold represents near and green represents far locations). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, localized changes were apparent in DV where near and mid- locations experienced almost 8 mm of accretion while the far location had less than 2 mm of accretion over the storm period (Fig. 5). Net surface accretion and accretion rate over the storm period were not statistically related to marsh elevation relative to MHW nor maximum storm height or duration.

### 4.4. Elevation change

Annual rate of elevation change prior to the storm was significant in four of the six marshes (Table 4b). Elevation change rates varied from an average of −3.5 mm/yr at IBSP to 8.4 mm/yr at DV. The negative trend at IBSP was influenced by an initial decline

**Table 3**
Bulk density and sand content of surface sediments following Hurricane Sandy in saline marshes within two estuaries in the mid-Atlantic, US. Values are means ± standard errors (n = 5).

| Estuary | Marsh | Depth interval (cm) | Bulk density (g/cm$^3$) | Sand (%) |
|---|---|---|---|---|
| Barnegat | RC | 0–2 | 0.07 ± 0.02 | 23 ± 3 |
| | | 2–4 | 0.08 ± 0.01 | 22 ± 2 |
| | IBSP | 0–2 | 0.15 ± 0.04 | 30 ± 8 |
| | | 2–4 | 0.14 ± 0.05 | 36 ± 12 |
| | CC | 0–2 | 0.10 ± 0.02 | 12 ± 2 |
| | | 2–4 | 0.11 ± 0.03 | 21 ± 6 |
| Delaware | DV | 0–2 | 0.08 ± 0.02 | 8 ± 2 |
| | | 2–4 | 0.11 ± 0.02 | 10 ± 4 |
| | MR | 0–2 | 0.13 ± 0.03 | 6 ± 1 |
| | | 2–4 | 0.20 ± 0.03 | 16 ± 10 |
| | DN | 0–2 | 0.14 ± 0.04 | 13 ± 6 |
| | | 2–4 | 0.16 ± 0.03 | 29 ± 15 |

approach a 1:1 relationship with 2013 elevations being very similar to that found in the previous year (Fig. 6). Surveyed elevations in the other three marshes differed between years. These marshes tend to have more of a hummocky topography (e.g. RC and DN), making small horizontal errors prone to much larger elevation errors. Thus, while these data were intended to illustrate variation in time, they are more reflective of micro-spatial variation in marsh topography. None of the marshes had a consistent change in elevation (or slope), with changes from 2012 to 2013 occurring both in positive and negative directions.

### 4.6. Vegetation characteristics

Changes in species composition and mid-summer biomass following Hurricane Sandy were spatially localized within marshes.

**Table 4**
Surface accretion (a) and surface elevation change (b) rates calculated over annual (linear regression), and daily (average of measurement intervals) time scales in three marshes of the Barnegat Bay and three marshes in the Delaware Estuary, New Jersey (n = 3, ±standard error). Net change and post-storm change rate were calculated using the difference between measurements immediately prior to and following the Fall 2012 storm events.

| Estuary | Marsh | Annual rate (mm/yr) | Pre-storm daily rate of change (mm/d) | Net change (H urricane, mm) | Post storm change rate (mm/d) |
|---|---|---|---|---|---|
| a) | | | | | |
| Barnegat | RC | 7.0 ± 1.0* | 0.05 ± 0.01 | −0.4 ± 5.3 | −0.15 ± 0.06 |
| | IBSP | 4.0 ± 2.0 | 0.03 ± 0.05 | −3.3 ± 4.8 | −0.02 ± 0.14 |
| | CC | – | 0 | 0 | 0 |
| Delaware | DV | 17.0 ± 4.9* | 0.04 ± 0.01 | 5.8 ± 3.6 | 0.30 ± 0.12 |
| | MR | 9.8 ± 3.5* | 0.02 ± 0.01 | 2.3 ± 2.9 | 0.05 ± 0.03 |
| | DN | 5.4 ± 1.6* | 0.05 ± 0.01 | 0.3 ± 2.9 | 0.01 ± 0.03 |
| b) | | | | | |
| Barnegat | RC | 6.9 ± 2.3* | 0.08 ± 0.02 | 5.6 ± 17.5 | 0.25 ± 0.76 |
| | IBSP | −3.5 ± 1.0* | −0.02 ± 0.01 | 3.6 ± 1.0 | −0.07 ± 0.02 |
| | CC | 5.5 ± 0.7* | 0.01 ± 0.02 | 0.9 ± 0.4 | −0.02 ± 0.01 |
| Delaware | DV | 8.4 ± 2.4* | 0.04 ± 0.03 | 6.8 ± 2.4 | 0.31 ± 0.11 |
| | MR | 3.2 ± 1.7 | 0.03 ± 0.01 | −21.2 ± 2.9 | −1.06 ± 0.14 * |
| | DN | 1.4 ± 1.8 | 0.01 ± 0.01 | 0.5 ± 1.8 | −0.02 ± 0.08 |

*Significantly different from zero (p > 0.05).
– Too few data points for trend analysis.

across all near, mid- and far locations (Fig. 4). Over the storm period, only MR experienced significant elevation change, which ranged from −15 to −24 mm ($t = -7.36$, $p = 0.0018$). The surface depression at MR was temporary such that the marsh surface had rebounded to pre-storm elevations by April (Fig. 5). Similar to surface accretion, elevation change was also spatially variable within marshes. For example, RC experienced an increase of 40 mm over the storm period at the far location, while near and mid-locations experienced no change and a decline in elevation, respectively. The increase in elevation over the storm period at RC far location was over four times greater than the increase in surface accretion, indicating that the elevation increase was associated with subsurface soil expansion, which subsequently subsided to pre-storm elevations within five months (Fig. 4). Over the long-term, there was no apparent impact of the 2012 storms, as elevations and regression slopes pre- and several months post-storm were not significant.

### 4.5. Elevation survey

Repeated elevation surveys were used to increase the spatial scale of measurement for evaluating potential storm impacts. Reoccupation of survey points collected in the summer of 2012 in the summer of 2013 revealed that the utility of this approach may be variable, depending on the spatial consistency (≥1 cm precision) and microtopography of the survey locations. For example, only two of the five marshes had a trend for successive elevations to

The greatest change in biomass and species composition occurred at RC in Barnegat Bay where *Spartina patens* was a dominant species far from the estuary prior to the storm (Fig. 7). In the summer following the fall storms, live and standing dead biomass were over 89% lower than that in the previous two summers ($F_{2,6} = 8.75$, $p = 0.0166$ and $F_{2,6} = 28.71$, $p = 0.0008$, respectively; Fig. 7). A reduction in biomass of both *S. patens* and *S. alterniflora* in 2013 was coincident with an increase in live *D. spicata*. At the barrier island marsh, IBSP, *Salicornia virginica* biomass was significantly greater in 2013 than in previous years at the far location. Here, both *S. alterniflora* and *S. virginica* were on average 10 cm taller in 2013 than in previous years ($F_{2,6} = 18.9$, $p = 0.0105$; Table 5). Few changes were observed in the Delaware Estuary marshes with respect to vegetation. At MR, one of the two locations had greater live biomass of *S. alterniflora* in the summer following Hurricane Sandy than in the two years prior ($F_{2,6} = 15.95$, $p = 0.0040$; Fig. 7) associated with an increase in shoot height ($F_{2,6} = 25.21$, $p = 0.0012$; Table 5).

## 5. Discussion

An assessment of aerial photographs from before and after Sandy suggested potential severe and long-term degradation of wetlands in Barnegat Bay (Hauser et al., 2015) at areas that included our study sites. In contrast, our field-based data suggests that the effects of Sandy on coastal salt marshes were localized, minor in magnitude, and short-term. The intense power of the storm was

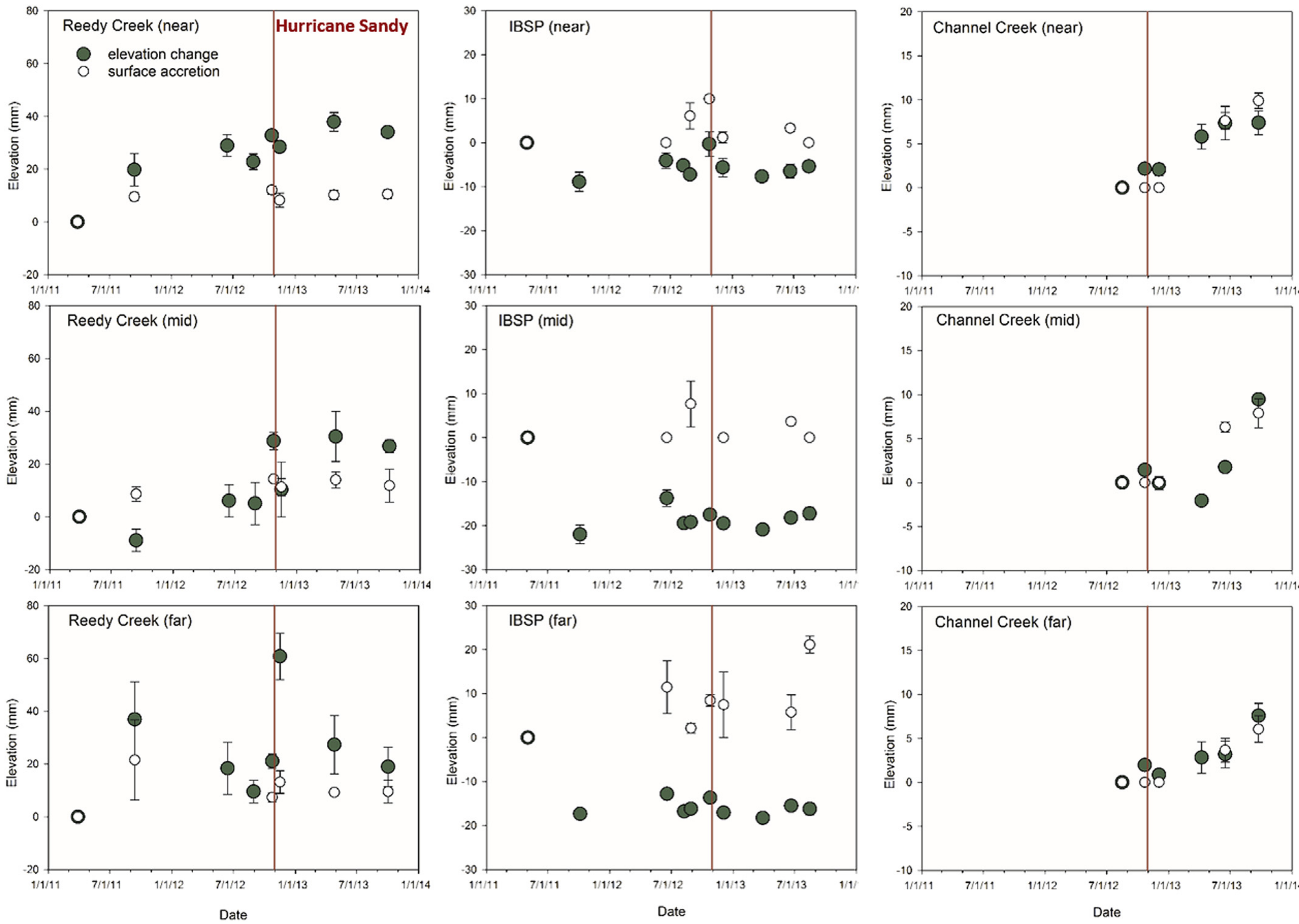


**Fig. 4.** Surface accretion and elevation change in marshes of Barnegat Bay, NJ before and after the passage of Hurricane Sandy on 29 October 2012, represented by a red vertical line. Values are means ± standard errors (n = 3). Note y-axis scales differ among marshes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

observed in the field with isolated scatterings of boats and debris on the marsh and at the adjacent tree line. However, there was no evidence of widespread wrack, sediment deposition or vegetation removal at any of the six marshes studied, despite high and prolonged water levels. Our field data indicated that the impacts of Hurricane Sandy and the following northeaster, which could not be distinguished, consisted of localized and temporary changes in elevation and peak season biomass, and the removal of standing biomass in the marsh farthest from the storm track where water levels were highest. Based on our observations of wrack along the tree line and developed structures in Barnegat Bay, we hypothesize that much of the material carried by the flood waters of the storm passed over the marsh and were concentrated and deposited along areas of taller structure than marsh grass. Sediments and organic debris were likely deposited where vegetation and infrastructure created resistance to flow along more of the flood water depth profile. A similar set of circumstances occurred during Hurricane Hugo in 1989 where, despite its intensity, Hugo had little impact on low-lying coastal marshes of South Carolina (Gardner et al., 1992). Similar to Hurricane Sandy, Hugo's approach was perpendicular to land and caused extreme water levels over the marsh. Localized effects of Hugo included the transport of dead *Spartina* biomass into the adjacent forest, where it was deposited as mats of detritus. Although Hugo had little effect on salt marshes, the storm created overwash fans on the barrier island and caused salinization of coastal forest soils and blackwater streams. High storm surge during Hugo (3–4 m) was hypothesized to have protected the marsh from wind, wave action and currents (Gardner et al., 1992). In addition, compared to freshwater wetlands, salt marshes have been described to be more resilient to erosional storm forces due to high soil shear strengths (Barras, 2006; Howes et al., 2010). Other storm characteristics such as the overlap of maximum wind speeds and storm surge, and coastal geomorphology, particularly the presence of barrier islands, are also likely to play a key role in reducing storm impacts on marshes.

### 5.1. Water level

Water levels in coastal marshes of New Jersey during Hurricane Sandy seemed to be related to geomorphology and location relative to storm rotation and wind direction. The influence of geomorphology on tidal signatures was evident during both Hurricane Sandy and the northeaster, where tidal dynamics were more prominent in the Delaware Estuary where there is greater exchange with ocean water than in Barnegat Bay. Peak water levels in the Delaware Estuary during Sandy were highest closer to the estuary mouth than farther up-bay and secondarily, closer to the mouths of tidal creeks than farther upstream. The highest water levels overall were measured in RC in northern Barnegat Bay despite being farthest from the storm track. Maximum water level measured in

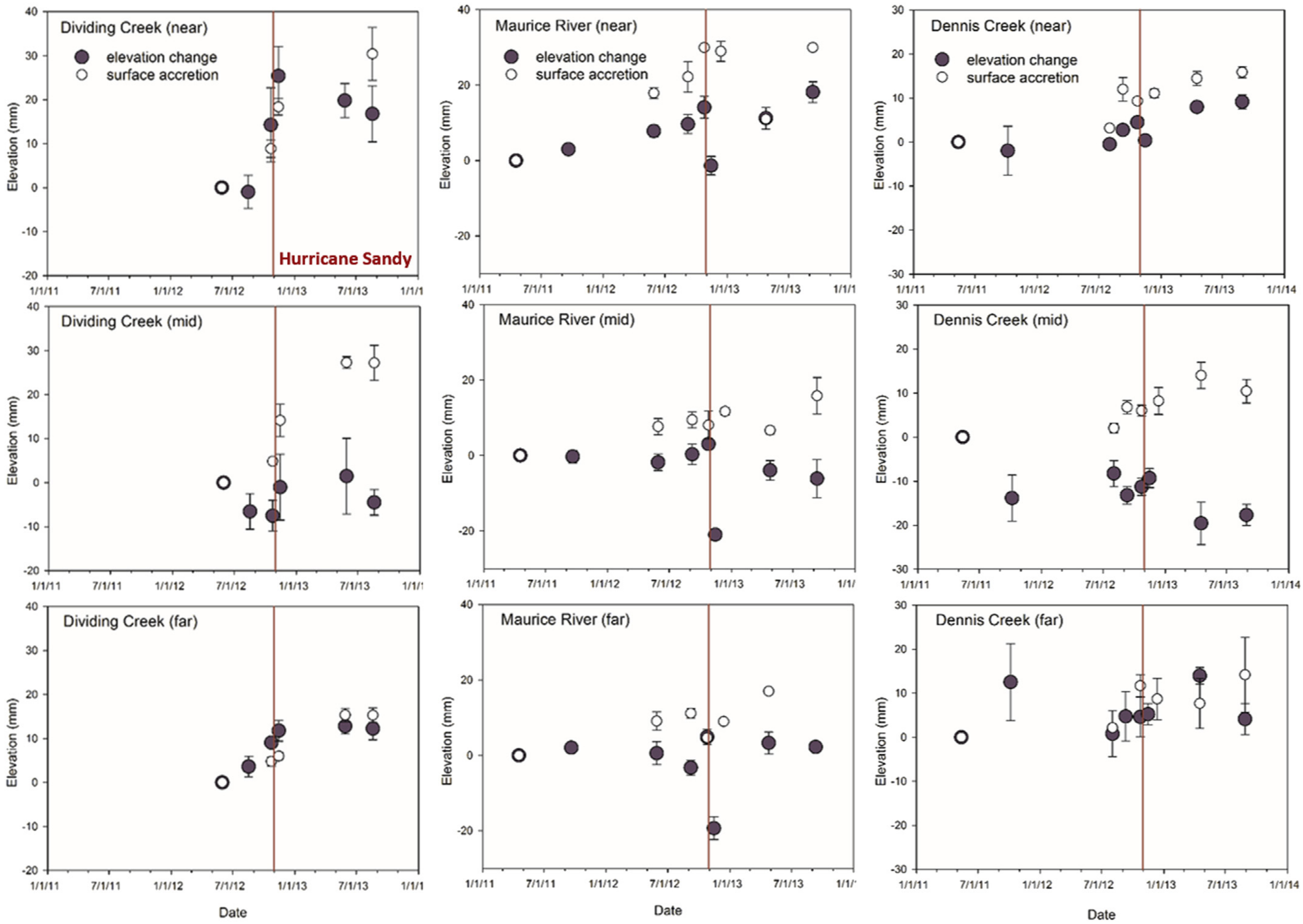


**Fig. 5.** Surface accretion and elevation change in marshes of Delaware Bay, NJ before and after the passage of Hurricane Sandy on 29 October 2012, represented by a red vertical line. Values are means ± standard errors (n = 3). Note y-axis scales differ among marshes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the RC marsh was approximately 15 cm lower (1.96 m, NAVD88) than that measured at the Mantoloking tide gauge (2.11 m, NAVD88; Miselis et al., 2015) suggesting some dissipation, although there may be some error in our peak water level extrapolation. High water level at RC relative to the other marsh sites may have been associated with both the breaching of the inlet at Mantoloking and Sandy's shift in wind direction from northerly at landfall to southerly post-landfall (Miselis et al., 2015). The rapid increase in water level in the northern part of Barnegat Bay has been attributed to a change in wind direction, while the southern part of Barnegat Bay experienced large tidal oscillations similar to the ocean tides (Miselis et al., 2015). The bayside of the barrier island at IBSP experienced lower water levels but a similar duration of flooding to that at RC during Sandy. This may be expected as the winds shifted from the northeast to the south, likely pushing water westward away from the barrier islands.

### 5.2. Surface soil, accretion and elevation change

Randomized collection of cores across the marshes, suggested little widespread deposition of sediments over the storm period. For sediment deposition to occur, several conditions need to be met, including a reduction in sediment carrying capacity of floodwaters. Resistance from vegetation can dampen tidal flow, waves, and currents, and allow sediments to drop out. Coarse-grained sediment deposition is hypothesized to be deposited with an abrupt initial water level change, followed by fine-grained deposition during water level decline as the storm moves landward (Halford, 1995). Although the composition of storm deposits can be quite variable, reflecting sediment sources ranging from bay-bottom and nearshore fine silts (Cahoon et al., 1995a) to coarse grained sands (Nyman et al., 1995) to scoured marsh soil indistinguishable from pre-storm deposits (Mckee and Cherry, 2009), storm signals were not apparent from visual inspection or bulk density and grain size of surface sediments (0–4 cm). Bulk densities of storm deposits in salt marshes in Louisiana range from 0.15 to 1.22 g/cm$^3$, with the average around 0.5 g/cm$^3$ (Mckee and Cherry, 2009). While some bulk densities of surface sediments collected in marshes in Barnegat Bay and the Delaware Estuary were within the range of storm deposits, they fell well below the average. Mineral lenses in sediment cores are often associated with storm deposits distinguished by higher bulk densities. Bulk densities above 0.4–0.8 g/cm$^3$, similar to bay bottom sediment bulk densities, were associated with storm deposits (DeLaune et al., 1978) rather than marsh soils, which averaged <0.30 g/cm$^3$ in Louisiana (Nyman et al., 1995). The likelihood of a storm signal was predicted to have been greater in IBSP, where eroded dunes covered the road landward of the marsh. In general, sand can be deposited far from dunes and overwash channels and up to a few hundred meters from the marsh edge (de Groot et al., 2011). Although shoreline

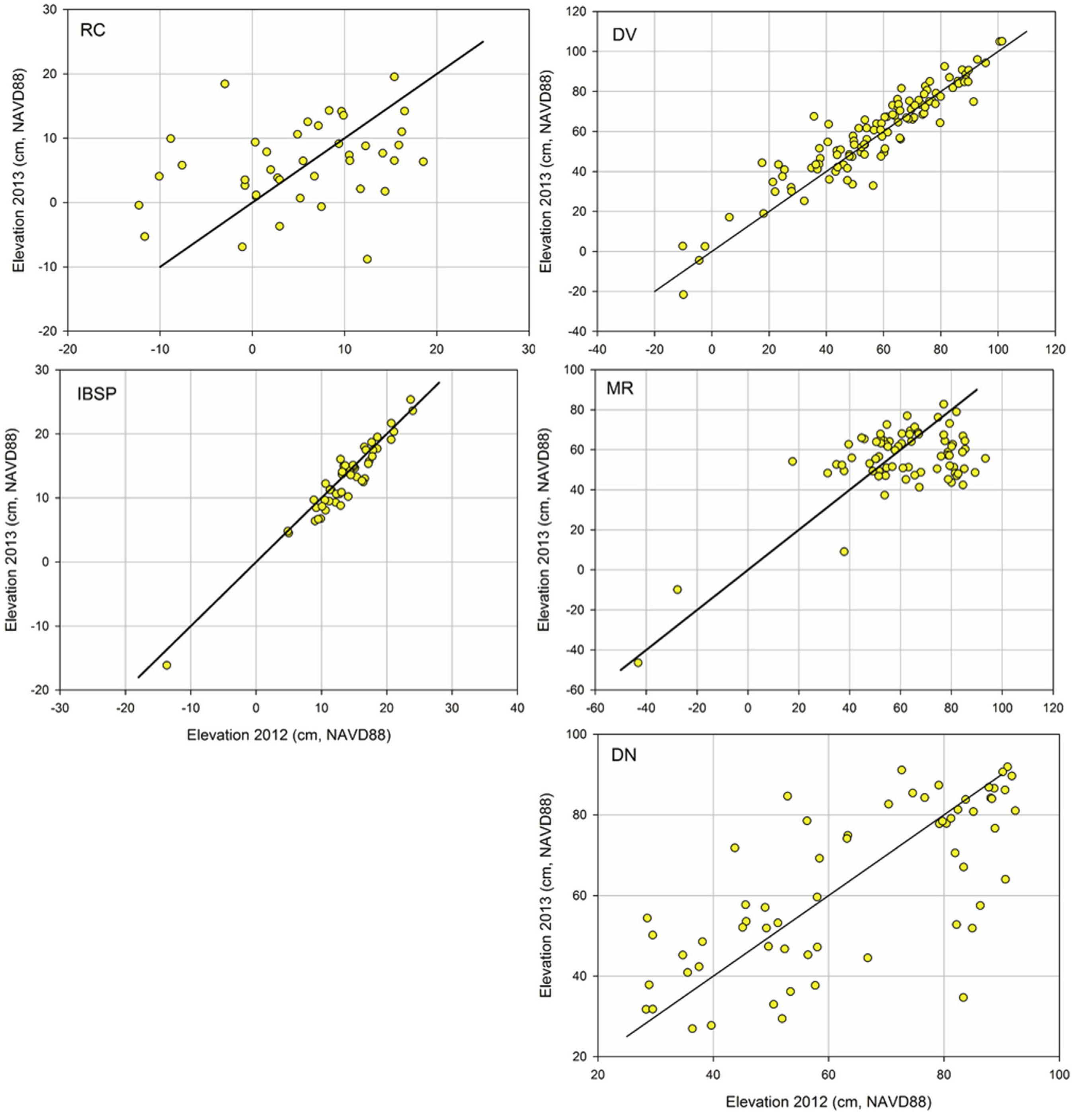


**Fig. 6.** Relationship between marsh elevation data collected in 2012 and 2013. Solid line represents a 1:1 relationship.

retreat and changes in dune height occurred along the barrier island in Barnegat Bay, few changes if any were observed in the relatively undeveloped Island Beach State Park (Miselis et al., 2015). In addition, subtidal changes to estuarine bathymetry were also highly localized adjacent to breaches in the barrier island or in discrete areas along the perimeter of the bay (Miselis et al., 2015).

Marsh surface and elevation changes were variable within marshes and across the region and, as others have found, storm events had little influence on longer-term elevation trends (e.g., Rogers et al., 2013). Overall, changes in elevation were documented in two locations in two of the six marshes. Elevation changes in both marshes were associated with temporary subsurface changes. Interestingly, in a review of marsh elevation responses to 15 hurricanes, soil elevation changes were most frequently associated with sub-surface processes rather than surface deposition or erosion (Cahoon, 2006). A distinct subsurface elevation change was observed at one of the study marshes, MR, where elevations temporarily declined by 15–24 mm, likely associated with compaction from the compression of air-filled soil pore spaces from the weight of the overlying storm tide waters (Cahoon, 2006). Compaction was more likely than soil shrinkage as soil organic matter content was relatively high (averaging 13–24% to 30 cm

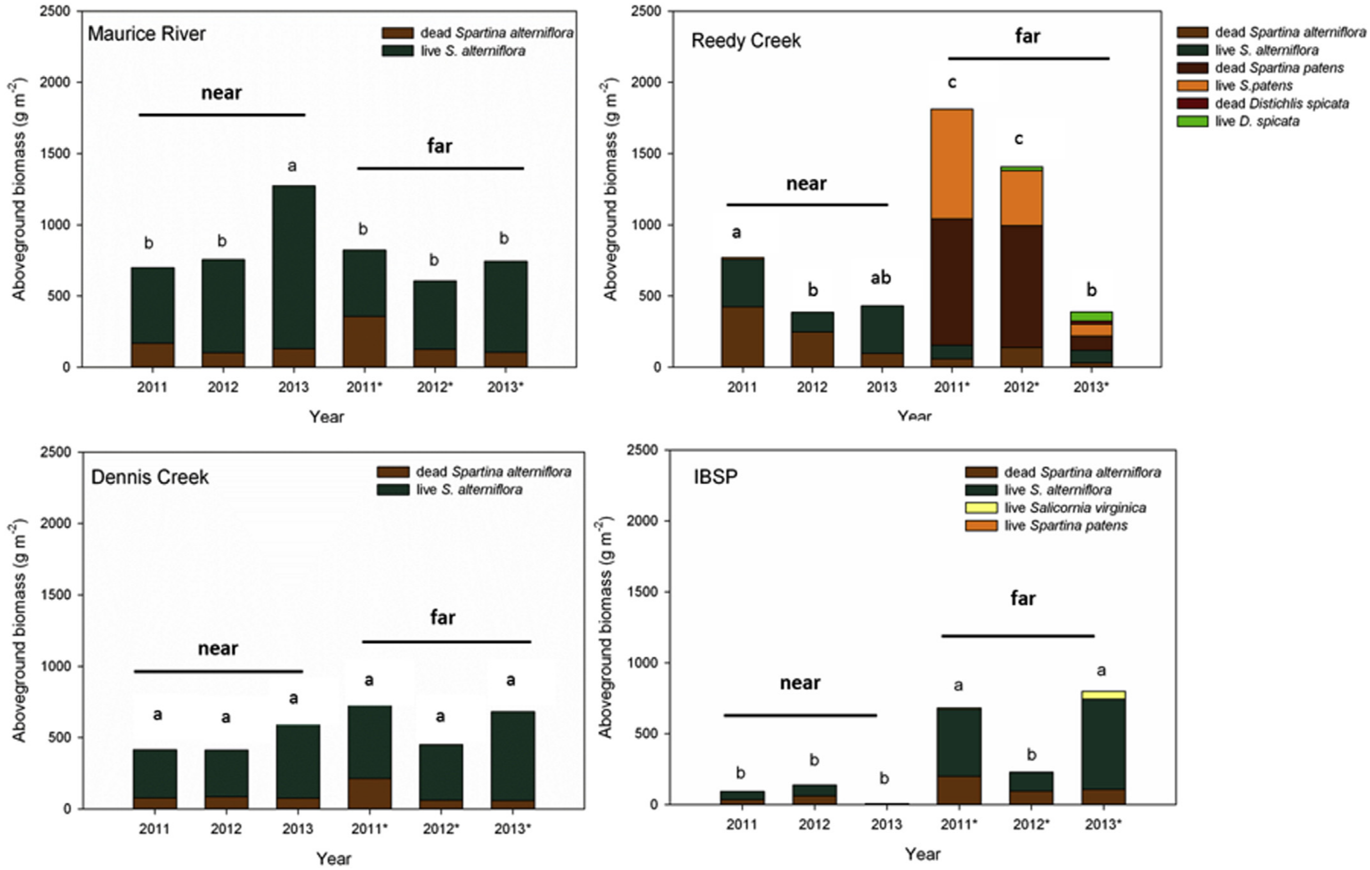


**Fig. 7.** Live and dead aboveground biomass of plant species in July/August of the two years prior to and the year following Hurricane Sandy in four marshes. Biomass was collected both near and far from the estuary. Values are means averaged over three replicate plots.

**Table 5**
Stem density and average shoot height in marshes near and far from the estuary in Barnegat Bay and Delaware Estuary, NJ. Values are means ± standard errors. Values represented by different letters are significantly different ($p < 0.05$) within marsh and parameter.

| Estuary | Marsh | Relative location | Stem density (#/m$^2$) | | | Stem height (cm) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 2011 | 2012 | 2013 | 2011 | 2012 | 2013 |
| Barnegat | RC | near | 527 ± 157 | 879 ± 437 | 960 ± 311 | 25 ± 2$^{ab}$ | 18 ± 1$^{a}$ | 30 ± 2$^{b}$ |
| | | far | 1494 ± 707 | 2514 ± 1071 | 1018 ± 642 | 50 ± 5$^{b}$ | 29 ± 2$^{a}$ | 24 ± 3$^{a}$ |
| | IBSP | near | 544 ± 327 | 1521 ± 682 | 288 ± 60 | 9 ± 1$^{a}$ | 11 ± 1$^{b}$ | 17 ± 2$^{c}$ |
| | | far | 991 ± 441 | 959 ± 374 | 1020 ± 406 | 17 ± 1$^{a}$ | 14 ± 2$^{a}$ | 29 ± 2$^{b}$ |
| Delaware | MR | near | 509 ± 78 | 760 ± 121 | 734 ± 103 | 44 ± 2$^{a}$ | 47 ± 3$^{a}$ | 81 ± 7$^{b}$ |
| | | far | 245 ± 23$^{a}$ | 429 ± 22$^{ab}$ | 777 ± 223$^{b}$ | 69 ± 2$^{b}$ | 46 ± 5$^{a}$ | 47 ± 8$^{a}$ |
| | DN | near | 1844 ± 268 | 1372 ± 243 | 945 ± 301 | 19 ± 1$^{a}$ | 28 ± 3$^{ab}$ | 47 ± 11$^{b}$ |
| | | far | 1467 ± 393 | 753 ± 118 | 671 ± 37 | 35 ± 8$^{ab}$ | 24 ± 5$^{a}$ | 53 ± 5$^{b}$ |

depth, PDE, 2012). While MR returned to pre-storm elevations within five months, compressed marshes may take two years to reach pre-storm elevations (Cahoon, 2006). Presumably the return to pre-storm elevations is associated with the re-gasification of soil spaces from microbial respiration (Cahoon, 2006) and/or slow diffusion during ebb tides. A second extreme localized elevation change occurred in RC, where elevation increased temporarily by 40 mm, with surface accretion accounting for 6 mm. These increases corresponded to major reductions in standing dead plant biomass in adjacent plots, which imply that the elevation increase at the SET may have been from the redistribution and deposition of locally removed plant material. An alternative and likely explanation is subsurface water flux into the marsh resulted in soil swelling (Cahoon, 2006), as there was over a meter of water on the marsh surface during the November SET measurements. By April, the marsh surface at this location had subsided to pre-storm elevations.

### 5.3. Vegetation changes

Vegetation changes in the summer following the fall 2012 storms were varied and localized within and among marshes. The most significant change in species composition and plant biomass occurred at RC where both standing dead and live biomass of *Spartina patens* was reduced by 90% compared to the previous two years. During the fall storms, both dead and live shoots from the previous growing season were likely present (e.g., Windham, 2001; Elsey-Quirk et al., 2011). Significant quantities of dead biomass of *S. patens* can accumulate from years of production and slow decomposition (Foote and Reynolds, 1997) forming dense mats. Storm related wind and water energy likely ripped up and removed material. The reduction in live biomass the following summer may have been due to both direct removal of live and dead shoots in the fall and/or a change in soil environment associated with the removal of accumulated biomass. During and at the end of the growing season, reserves of non-structural carbohydrates stored in rhizomes of *Spartina patens* are important for metabolism during the winter and early spring growth prior to the onset of photosynthesis (Gallagher and Howarth, 1987). Removal of live and dead biomass over the winter can result in plant death, potentially associated with the depletion of reserves for anaerobic metabolism or a lack of conduits for oxygen transport (Wijte and Gallagher, 1991). For *S. patens* in this study, the reserves necessary to facilitate spring growth may have been depleted with the removal of aerial biomass. In addition, the large clumps of accumulated dead shoots, which decompose slowly, function to shade the soil and create microsites of lower soil temperature. The removal of this plant cover may have allowed an increase in soil temperature and evaporation at the soil surface resulting in higher soil salinity in the summer. The reduction in biomass of *S. patens* was accompanied by an increase in *D. spicata,* a salt tolerant species common in disturbed areas (Hansen et al., 1976), suggesting a change in soil environment and/or an escape from direct competition with *S. patens* (Bertness, 1991).

With no evidence of storm deposition nor significant elevation changes at MR, the localized increase in mid-summer biomass due to an increase in plant height was likely associated with flushing and a change in porewater chemistry. Height of *S. alterniflora* also increased at IBSP, although height increase did not affect any changes in biomass. Plant height can be particularly plastic, responding quickly to local environmental conditions. *Spartina alterniflora*, tends to be taller and more productive lower in the tidal frame (Morris et al., 2002) and following a flooding disturbance, which can increase nutrients and facilitate porewater exchanges (Caetano et al., 2012). The long-term consequences of these localized changes in plant biomass and species distributions will be highly dependent on future climatic conditions and sea level.

## 6. Conclusions

Hurricane Sandy generated a large surge, which caused flooding and wind damage in 24 states and estimated economic losses of tens of billions of dollars (New York City, 2013; FEMA, 2013). Along the coast of New Jersey, barrier islands were breached, depositing sediments into the subtidal shallows, dunes were eroded creating overwash fans, and coastal marshes experienced prolonged flooding and storm tide conditions (Miselis et al., 2015). While major storms can have pronounced and long-term effects on coastal wetlands, our field data suggest that Hurricane Sandy and the northeaster that followed had localized and, for the most part, temporary impacts on salt marshes of New Jersey. This information is important for predicting and modeling future storm impacts and for local wetland managers to understand the role of storms in marsh dynamics. Hurricane Sandy was the 10th hurricane of 2012 and the frequency of large hurricanes are likely to increase.

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