Appendix 6
Using Sediment Elevation Tables to Analyze Recent Changes in Surface Elevation of New Hampshire Salt Marshes

Using Sediment Elevation Tables (SETs) to Analyze Recent Changes in Surface Elevation of New Hampshire Salt Marshes

Prepared for:

NEW HAMPSHIRE DEPARTMENT OF ENVIRONMENTAL SERVICES, NEW HAMPSHIRE COASTAL PROGRAM

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Using Sediment Elevation Tables (SETs) to Analyze Recent Changes in Surface Elevation of New Hampshire Salt Marshes

Introduction

Our perceived value of salt marshes has changed dramatically through the centuries. Once highly praised for support of fisheries and a source of fodder for cattle, marshes fell out of favor in the early 20th century and were filled for parking lots, wastewater treatment and landfills. More recently, we have recognized marshes have a suite of characteristics and functions that we value highly: support of fish and wildlife, erosion and flood control, nutrient cycling, and carbon storage. Another extraordinary ecosystem service that is rarely recognized is the ability of marshes to maintain themselves - to build in elevation as sea level rises without any help from us.

Sea level has been rising for the past 10,000 years in New England. Salt marshes developed along our shores about 4,500 years ago and those that are still around today have been building in elevation ever since. If you gaze across a large marsh, you may come to realize that the marsh's flat surface is a product of high tides depositing sediments evenly across it. As seawater floods the marsh, sediments are deposited onto the marsh surface and this process is enhanced by filtering grasses (Stumpf 1983). Sedimentation combined with root and rhizome production gradually form organic rich sediments, called peat. Every year the process continues, adding 1 to 3 mm to the marsh surface. With sea level expected to rise at rates exceeding 5 mm per year in the coming decades (Nicholls and Cazenave 2010, Hay et al. 2015), we do not know whether marshes will be able to keep up. If marshes cannot, they will drown and we will lose the many benefits and services they provide (Craft et al. 2009; Chmura et al. 2012).

Over the past two decades, scientists from many institutions have developed a tool called the Surface Elevation Table or SET, to measure the change in elevation in our marshes. SETs are a non-destructive leveling device used to carry out precise changes of elevation in a fixed location within a marsh (Boumans and Day 1993). A SET is composed of two parts: a fixed subsurface benchmark, which is a continuous metal shaft driven into and through the marsh sediments to the point of refusal (preferably to bedrock) and a mechanical leveling arm that attaches to the benchmark. Rods are gently lowered through the mechanical leveling arm to abut the marsh surface and the vertical distance is measured for all nine rods. This process is repeated at four compass bearings and the 36 data points are averaged to determine marsh surface elevation at a precise location (Figure 1).

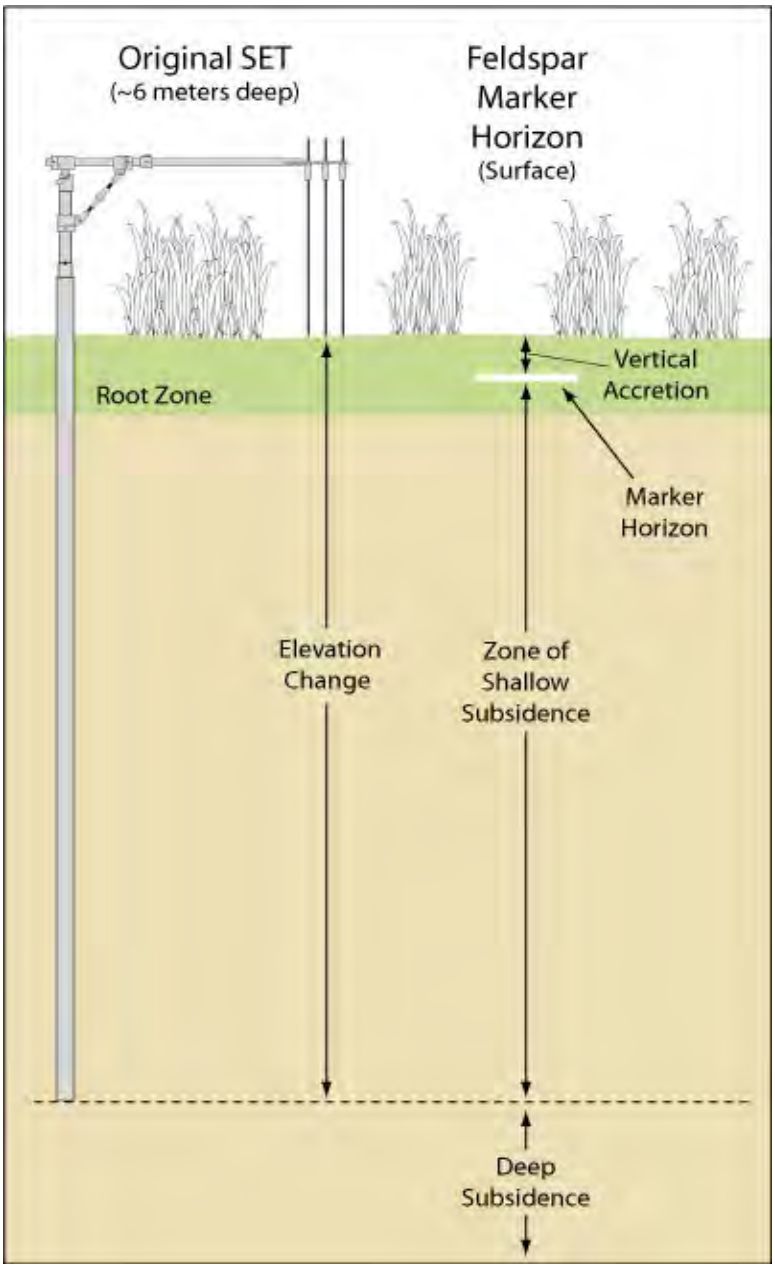

Figure 1. SET diagram. Image from Don Cahoon and Jim Lynch: http://www.pwrc.usgs.gov/set/

Measurements over time show how the marsh changes in elevation. Near each benchmark on the first day of measurements, a layer of white clay is deposited as a powder (feldspar) to mark the original marsh surface so we can determine the amount of sediment that collects on the surface over time. SET measurements combined with the depth to this marker horizon are able to measure total elevation change and can parse out the change due to surface deposition and subsurface processes. Near surface processes that affect

elevation include sedimentation, root growth and decomposition, whereas subsurface processes include compaction and decomposition.

Measurements taken from SETs can provide scientists and managers with a better understanding of how salt marshes have responded to sea level rise in the recent past to aid predictions for marsh response and survival in the future. Previously installed SETs and marker horizons in Great Bay (NH; Stacey et al. 2012) and the Webhannet River Estuary (Wells, ME; Burdick et al. 2013) show marshes have been building in elevation more rapidly over the past decade (2001-2011; Figure 2). The 4 to 5 mm yr^{-1} marsh growth indicated sea level was rising faster at our coasts than the global SLR rate of 3.6 mm/year (Nicholls and Cazenave 2010, Church and White 2011). We believe the rapid growth in marsh elevation was in response to a recently discovered and historically unprecedented jump in sea level of 128 mm during the period 2009-2010 (Goddard et al. 2015).

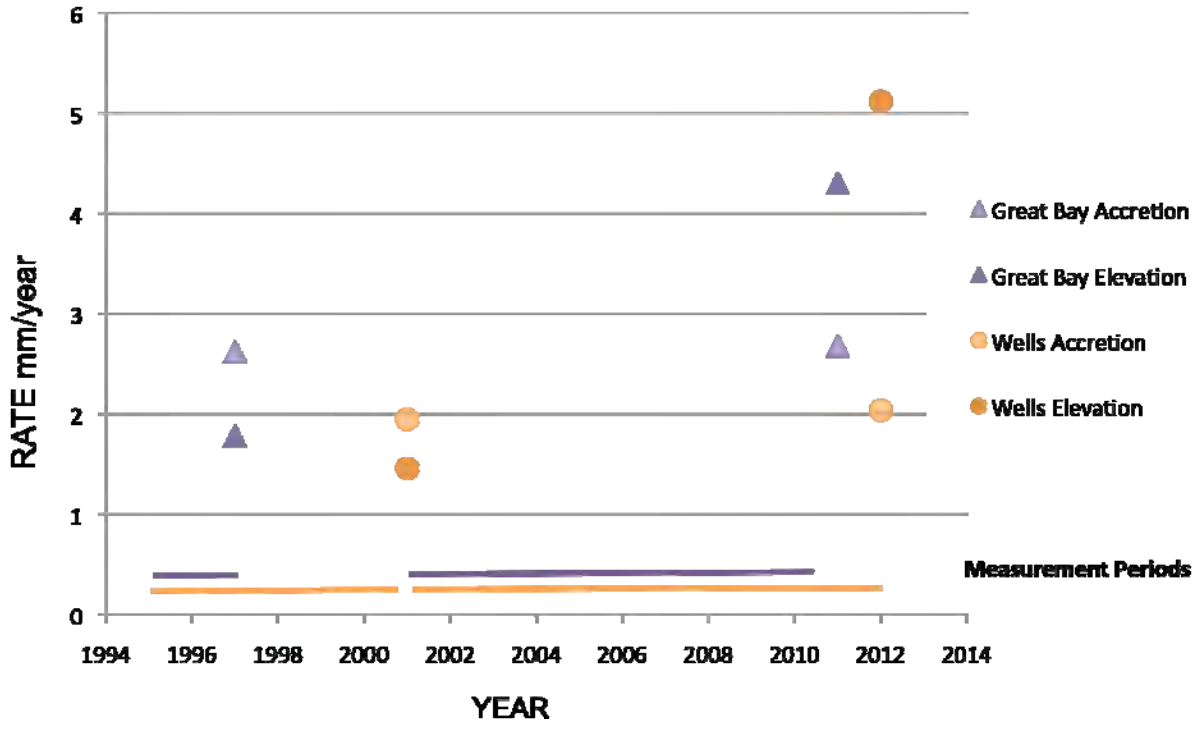

Figure 2. Rates of sediment accretion and surface elevation change in two Gulf of Maine estuaries. Note consistent accretion rates between the two periods (2.0 mm/yr in Wells and 2.7 mm/yr in Great Bay), but an accelerated rate of marsh building from < 2 mm/yr to almost 5 mm/yr.

Our research on salt marsh elevation is aimed to further our understanding of how salt marshes in New Hampshire respond to changing sea levels by examining recent (2011-14) changes in surface elevation at the major coastal systems in New Hampshire. SET

benchmarks existed in Great Bay and Awcomin Marsh from previous research efforts, but not in the Hampton Seabrook Estuary. Therefore, six new benchmarks were recently installed in Hampton Seabrook Estuary in anticipation of this project. The complete array of SET locations monitoring for the project are shown in Figure 3. To determine if elevation change was due to sediment accretion at the marsh surface or subsurface processes of peat preservation or decomposition resulting in subsidence, marker horizons were sampled. New SET measurements would allow comparisons of accretion and marsh elevation growth among the three major coastal systems in New Hampshire: Drowned River Valley (Great Bay), Barrier System (Hampton Seabrook Estuary) and smaller coastal inlet systems (represented by Awcomin Marsh at Rye Harbor).

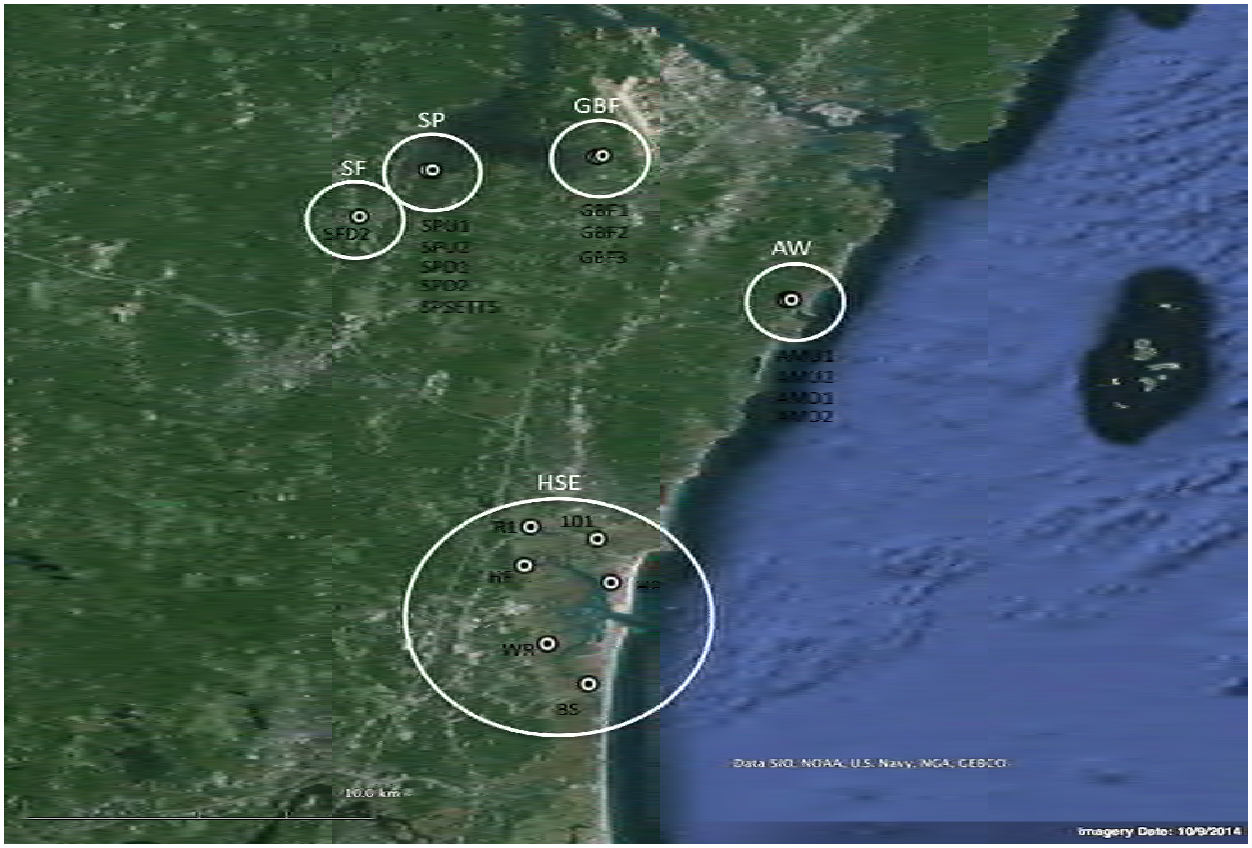

Figure 3. Locations of benchmarks established for Surface Elevation Table (SET) measurements of sediment accretion and marsh elevation change in New Hampshire.

Habitat elevation data of tidal marshes combined with SET data are important in predicting what habitat may be able to exist under a hypothetical sea level. For example, SLAMM (Sea Level Affecting Marshes Model) is a model that has been recently upgraded so such data can be used to predict impacts from sea level rise on tidal marsh habitat. The elevation at and around all SET stations relative to the tidal datum was undertaken to determine the

range of elevations that salt marshes exist at the Hampton-Seabrook Estuary. Salt marshes can be divided into low marsh, which is flooded daily by tides and dominated by smooth cordgrass, and high marsh, which begins at approximately the average high tide and extends upward to the surrounding uplands. In addition, the elevations of the SETs could be used to determine if differences in the rate of marsh surface elevation change was a function of its position in the intertidal zone (i.e., Do higher elevation sites accrete at a lower rate than lower elevation sites?).

Objectives and Activities

Our objectives for this project include collection and analysis of SET elevation and marker horizon data for New Hampshire marsh systems over the past 3 years. Habitat elevation would also be collected throughout the Hampton-Seabrook Estuary and compared to local tidal datums. In addition, we attended meetings to support and promote the project and provided advice to project partners on the types of habitats to include in coastal viewer and examined coastal viewer outputs.

Methods

SET Locations and Measurement Dates

Benchmarks for SET measurements had previously been installed several decades ago in the 1990s in Great Bay and Rye Harbor (Table 1). Installation of the benchmark was accomplished using a vibra-corer by driving aluminum pipe into the marsh to the point of refusal (see: http://www.pwrc.usgs.gov/set/SET/original.html). More recently, additional SETs were installed in Great Bay salt marshes for the Great Bay National Estuarine Research Reserve (GBNERR) sentinel site program. In anticipation of the Resilient NH coasts project, six SET benchmarks were installed in the Hampton-Seabrook Estuary (HSE), the largest contiguous salt marsh system in New Hampshire (Burdick and Peter 2014). New SET benchmarks were established by driving in stainless steel rods to the point of refusal (see: http://www.pwrc.usgs.gov/set/SET/rod.html). Marker horizons were established at the time of the first SET readings by applying 750 mL of feldspar evenly over a 30 by 30 cm area at two locations around each SET.

On the eastern side of the Great Bay Estuary, three SETs were installed in late 2011 at a tidal riverine system surrounded by forests and agriculture fields named Great Bay Farms (GBF) for the GBNERR (Figure 3). SETs were placed along an estuarine gradient ten meters from the high marsh edge that borders the main tidal creek. Marsh surface elevations were measured eight times from Dec 2011 to Nov 2014, and accretion four times from April 2013 to July 2014 (Table 1).

Waterbody	Geomorphic Setting	SET ID	Installation Date	Measurement Dates (Relative Elevation = E, Accretion = A)								
				Summer 2011	Fall 2011	Spring 2012	Spring 2013	Summer 2013	Fall 2013	Spring 2014	Summer 2014	Fall 2014
Great Bay Estuary	Riverine	GBF1	11/03/11		E, A	E	E, A	E, A	E, A	E	E, A	E
Great Bay Estuary	Riverine	GBF2	11/03/11		E, A	E	E, A	E, A	E, A	E	E, A	E
Great Bay Estuary	Riverine	GBF3	11/03/11		E, A	E	E, A	E, A	E, A	E	E, A	E
Great Bay Estuary	Embayment	SPD1	08/01/94	E, A		E		E, A	E, A	E	E, A	E
Great Bay Estuary	Embayment	SPD2	08/01/94							E	E, A	E
Great Bay Estuary	Embayment	SPU1	08/01/94	E, A		E		E, A	E, A	E	E, A	E
Great Bay Estuary	Embayment	SPU2	08/01/94	E, A		E		E, A	E, A	E	E, A	E
Great Bay Estuary	Embayment	SPSETT5	03/15/12			E, A		E, A	E, A	E	E, A	E
Great Bay Estuary	Riverine	SFD2	08/01/94			E, A				E	E, A	E
Hampton-Seabrook Estuary	Back-Barrier	BS	04/18/13					E, A	E	E	E, A	E
Hampton-Seabrook Estuary	Back-Barrier	HP	05/02/13					E, A	E	E	E, A	E
Hampton-Seabrook Estuary	Back-Barrier	HF	04/18/13					E, A	E	E	E, A	E
Hampton-Seabrook Estuary	Back-Barrier	R1	05/17/13					E, A	E	E	E, A	E
Hampton-Seabrook Estuary	Back-Barrier	101	05/17/13					E, A	E	E	E, A	E
Hampton-Seabrook Estuary	Back-Barrier	WR	04/18/13					E, A	E	E	E, A	E
Rye Harbor	Back-Barrier	AMD1	09/01/94			E, A		E, A	E	E	E, A	E
Rye Harbor	Back-Barrier	AMD2	09/01/94			E, A		E, A	E	E	E, A	E
Rye Harbor	Back-Barrier	AMU1	09/01/94			E, A		E, A	E	E	E, A	E
Rye Harbor	Back-Barrier	AMU2	09/01/94			E, A		E, A	E	E	E, A	E

Table 1. Station locations and sampling dates for Surface Elevation Tables (SETS) and Marker Horizons (MH) in New Hampshire.

On the western side of Great Bay Estuary, five SETs were installed near the Sandy Point Discovery Center (SPDC), a National Estuarine Research Reserve (GRB): SPD1, SPD2, SPU1, SPU2 in 1994 and SPSETT5 in 2012 (Table 1). The tidal marsh at SPDC is located directly on Great Bay (Figure 3). SPD1, SPD2 and SPETT5 were placed approximately 10 m from the high marsh edge that borders the bay, whereas SPU1 and SPU2 were placed in high marsh 50 m landward of Great Bay. Measurement records varied in duration and frequency at SPDC. A full set of measurements was taken for SPD1, SPU1, SPU2, which included 7 measurements of elevation and 4 measurements of accretion. SPD2 was buried in sediment and could not be located until the spring of 2014 following ice-out, but prior to plant growth. SPSETT5 was installed in March 2012 and measured regularly for elevation and accretion (Table 1).

Southwest of the SPDC by 2.8 km, four SET benchmarks were installed in Mill Creek Marsh at Stuart Farm in 1994. The tidal marsh at Stuart Farm (SF) is a tidal riverine system, with all SETs placed 10 m from the high marsh edge that borders the main tidal creek. High sedimentation (19 mm yr^{-1}; Burdick et al. 1999) has likely buried the entirety of all SET bases at two Stuart Farm upstream sites, making it very difficult to relocate them. As a result of burial and over 10 years between field visits, only one of the SET benchmarks (SFD2) has been relocated and measured to date (Table 1). The lone recovered Stuart Farm SET (SFD2) was measured for elevation four times and accretion twice.

In 1994, four SETs were installed at Awcomin Marsh, a back barrier salt marsh on the coast of New Hampshire (Figure 2). SETs were installed 10 m from the high marsh edge that bordered a tidal creek. Two SETs at Awcomin were placed in an area of tidal restoration (AMU1, AMU2) following dredge disposal in 1941 and 1962, and the other two (AMD1, AMD2) in a reference area (Burdick et al. 1999). Since 2012, marsh surface elevations and accretion were measured several times (Table 1).

In spring of 2013, six SETs were installed in tidal marshes throughout Hampton-Seabrook Estuary (HSE; Figure 2). Sites were chosen based on accessibility, avoiding proximity to ditches and gaining permission. Permission was obtained from private land-owners, owners of town lands (Seabrook, Hampton Falls, and Hampton) and NH Fish and Game for locations on state lands. SETs were installed 10 m from the high marsh edge bordering a tidal creek, and marsh surface elevations were measured 5 times and accretion once (Table 1).

Marsh Elevations

At Hampton Seabrook Estuary, elevation surveys were conducted at each SET in the summer of 2014. Ellipsoid height of SET benchmarks (top edge of receiving head) and survey discs (permanently placed in concrete adjacent to the SET base) were measured using a Real Time Kinematic system (RTK GPS), including a local base station. Multiple measurements were taken directly on the SET benchmarks for two minutes and RTK vertical precision ranged from 0.03 to 0.09 m. Ellipsoid heights were converted to NAVD88 (m) with NOAA's VDatum software, v.34. Data are preliminary until verified using a known USGS elevation marker. Tidal marsh elevations adjacent to the SETs were also surveyed by using a laser level, tripod and rod, and then tying into the SET benchmarks in 2014 and 2015. Multiple points were measured within and at the borders of different marsh zones (e.g., low marsh edge, high marsh, upland edge) to establish the elevation ranges for low and high marsh in the Estuary.

SET and MH Measurements and Analyses

SET elevations were determined by lowering nine pins to just touch the marsh surface and measuring the vertical distance in mm from the top of the pin to the SET arm at four positions around each benchmark. Elevations recorded and presented are relative to the SET base. Marsh surface elevations were averaged by bearing (n = 9 pins) and averaged to each SET (n = 4 bearings) for all dates measured from 2011 to 2014. Elevation change rates for each SET location were determined using linear regressions over time, including all dates recorded from 2011 to 2014. Means were calculated for each marsh system and overall for NH seacoast.

Surface accretion was determined by cutting a pie-shaped wedge of marsh (10 by 5 by 5-7 cm deep) from the marker horizon plot. The wedge was extracted and the vertical distance between the marsh surface and the top of the marker horizon was measured using vernier calipers (+/-0.1 mm). Variation in marker horizon depth was modulated by selecting the mode for each side of the wedge (up to three measurements) that were averaged for the plot. Each SET had 2 feldspar marker horizon plots positioned 180° apart – on either side of the SET base. Then the two plots were averaged for the SET location. Accretion rates for each SET location were determined using linear regressions of changing depths over time, including all dates recorded from 2011 to 2014. The same averaging process was conducted for accretion rates, calculating average rates for each marsh system and NH.

The data collected were input to a standardized database which was made available to others by creating a metadata file to accompany each dataset generated (SET and Marsh Elevation) and submitting to NOAA and GBNERR. The metadata was developed to be compliant with the Federal Geographic Data Committee's Content Standard for Digital Geospatial Metadata (CSDGM) and will be checked with NH Coastal Program for adherence to standards.

Results

Marsh surface elevation and sediment accretion were measured using 19 SET stations on a regular basis since 2011 in the two major estuaries and one smaller marsh system of New Hampshire. On average, marshes increased in surface elevation by 2.3 ± 0.7 mm yr^{-1}. The average sediment accretion rate was very similar (2.4 ± 0.9 mm yr^{-1}) and accounted for all of the elevation change we observed (Figure 4). Sub-surface changes to peat under the marker horizon, such as accumulation vs. decompostion and compaction, is determined by subtracting the accretion from the surface elevation change. The overall difference averaged -0.1 mm yr^{-1} for our measurements. Since the difference is close to '0', it appears the processes that build and degrade peat were about equal from 2011 to 2014.

When examining elevation change among salt marsh systems in NH, most marshes built up at similar rates (sites in Great Bay and HSE), ranging from 2.1 to 2.6 mm yr^{-1}. However, the small back barrier Awcomin Marsh deviated from this range at both downstream and upstream areas of the marsh. The SET and marker horizon results are examined for each marsh system separately in the following paragraphs.

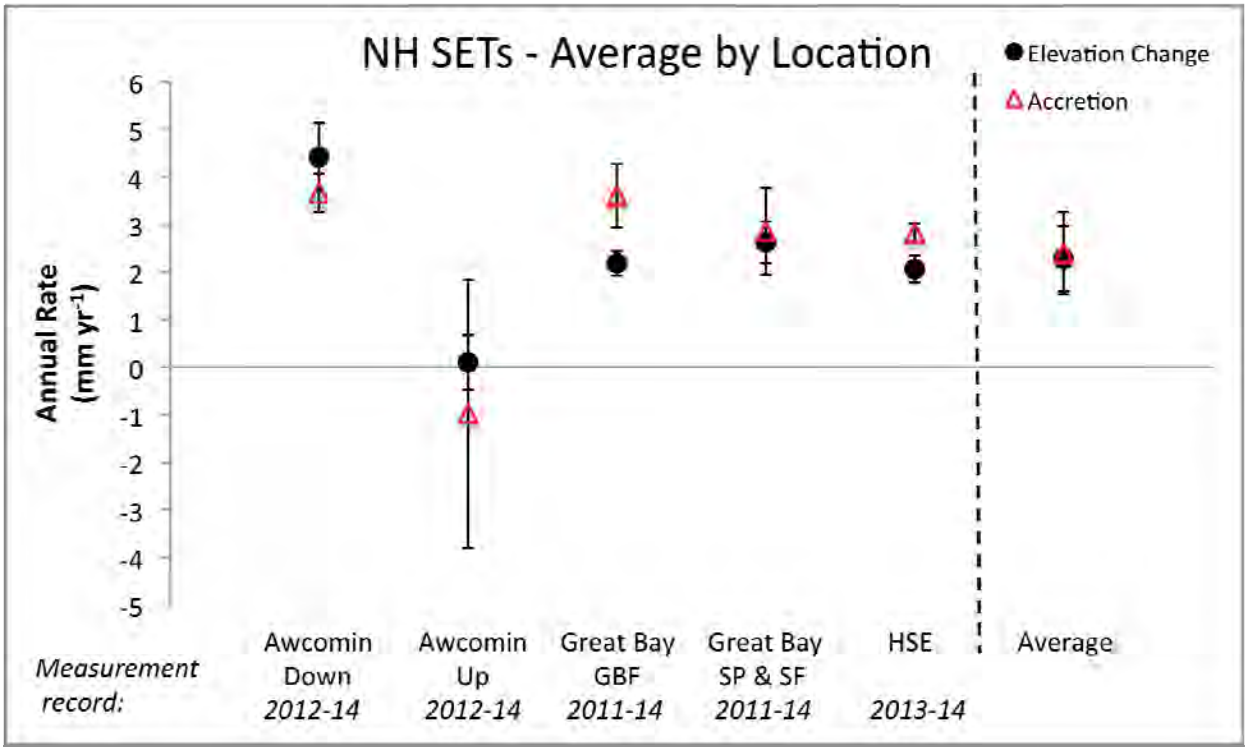

Figure 4. Rate of surface elevation gains (circles) and accretion (triangles) averaged by marsh system with standard error bars (except for Awcomin Marsh) as well as for the entire state.

On the eastern side of the Great Bay Estuary, all three SET stations at Great Bay Farms (2011-14) showed similar increases in elevation. A linear regression of each SET was used to calculate the rate of change (i.e., slope over time), which averaged 2.2 ± 0.3 mm yr^{-1} (Figure 5). Accretion rates showed consistent building over time ($r^2 > 0.90$), but variable across stations, with the downstream stations, GBF1, showing greater accretion rates than the other two SETs (Figure 6). Since we found the average accretion rate was considerably higher than the elevation change rate, we interpret the marsh was building solely from additions of sediment to the marsh surface, with belowground processes of compaction and decomposition dominating.

On the western side of Great Bay at SPDC and Stuart Farm, increases in marsh surface elevation ranged from 1.1 to 3.9 mm yr^{-1} and averaged 2.6 ± 0.4 mm yr^{-1} (Figure 7). SPSETT5 and SFD2 had the largest increases in elevation. SPU1 and SPU2, which are located farther up the marsh gradient in the high marsh had the lowest increases in elevation (similar to our results for GBF marsh). When excluded (SPU1 and SPU2), the average annual change in elevation was 3.2 ± 0.3 mm yr^{-1}. Surface accretion was quite variable for SPDC and Stuart Farm sites, with an average of 2.9 ± 0.9 mm yr^{-1} (Figure 8). Accretion rates were slightly greater than elevation change (2.9 vs. 2.6 mm/yr) suggesting peat compaction and decomposition were greater than accumulation and growth during this sampling period.

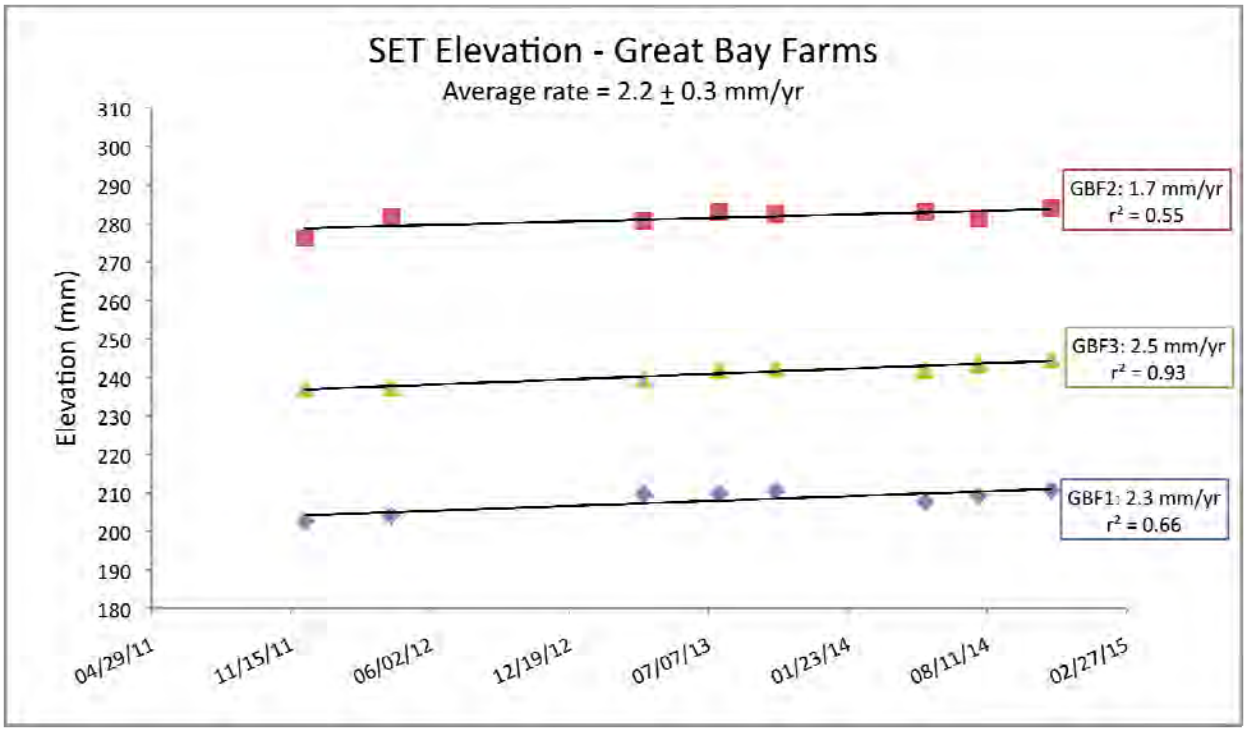

Figure 5. Changes to surface elevation for Great Bay Farms marsh in eastern Great Bay. Note: GBF2 elevations were increased by 40mm to facilitate visual comparison with other SETs.

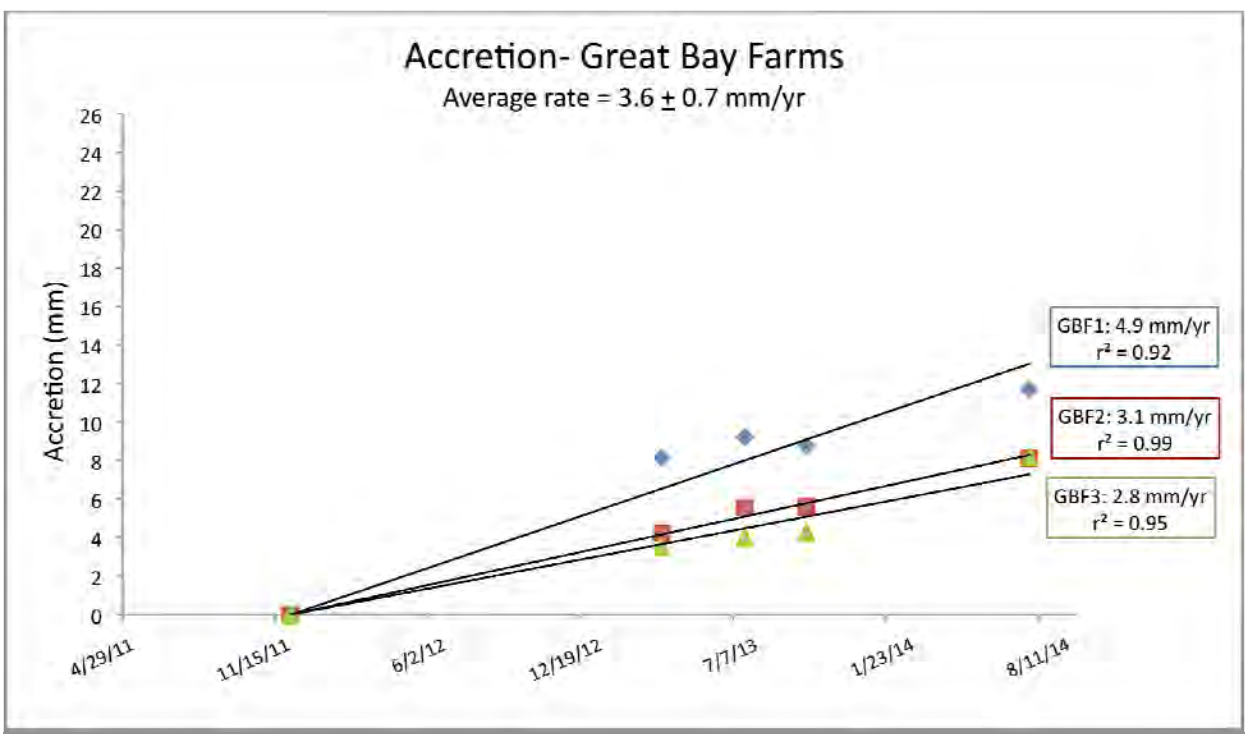

Figure 6. Sediment accretion over marker horizons for Great Bay Farms marsh in eastern Great Bay.

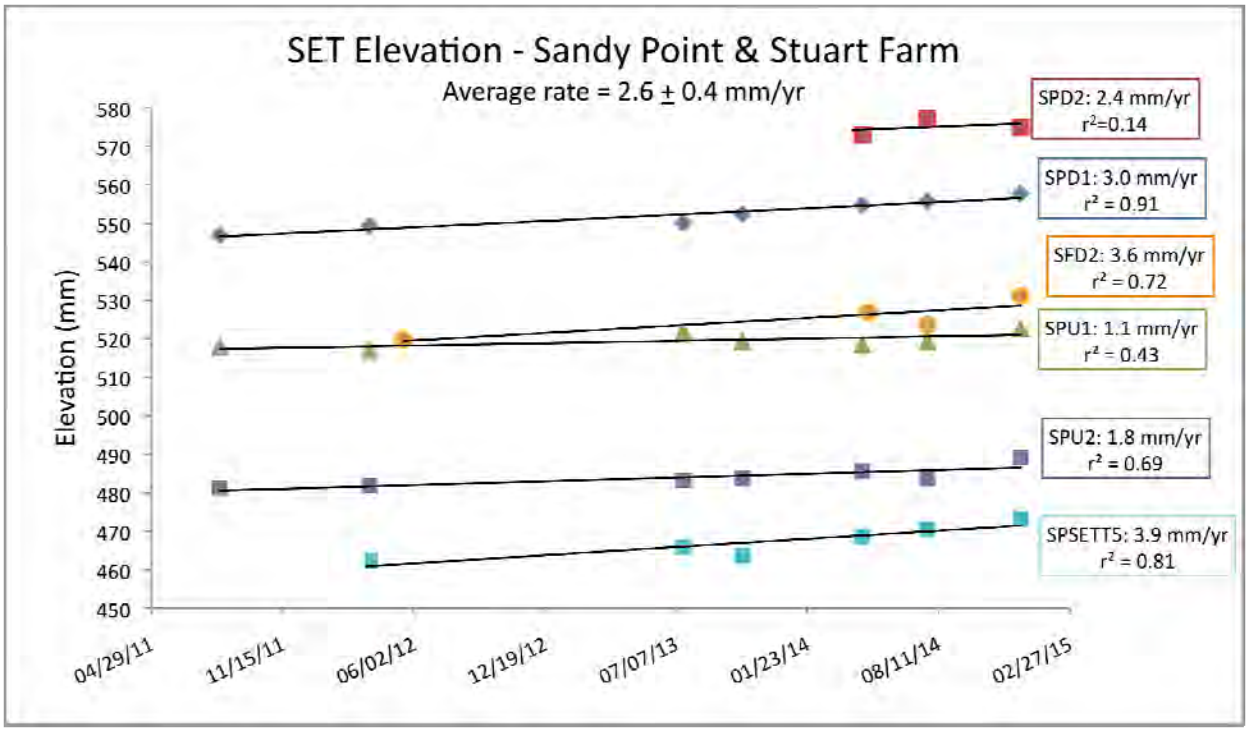

Figure 7. Changes to surface elevation for Sandy Point and Stuart Farm marshes in western Great Bay. Note: SPSETT5 elevations were increased by 225mm to facilitate visual comparisons.

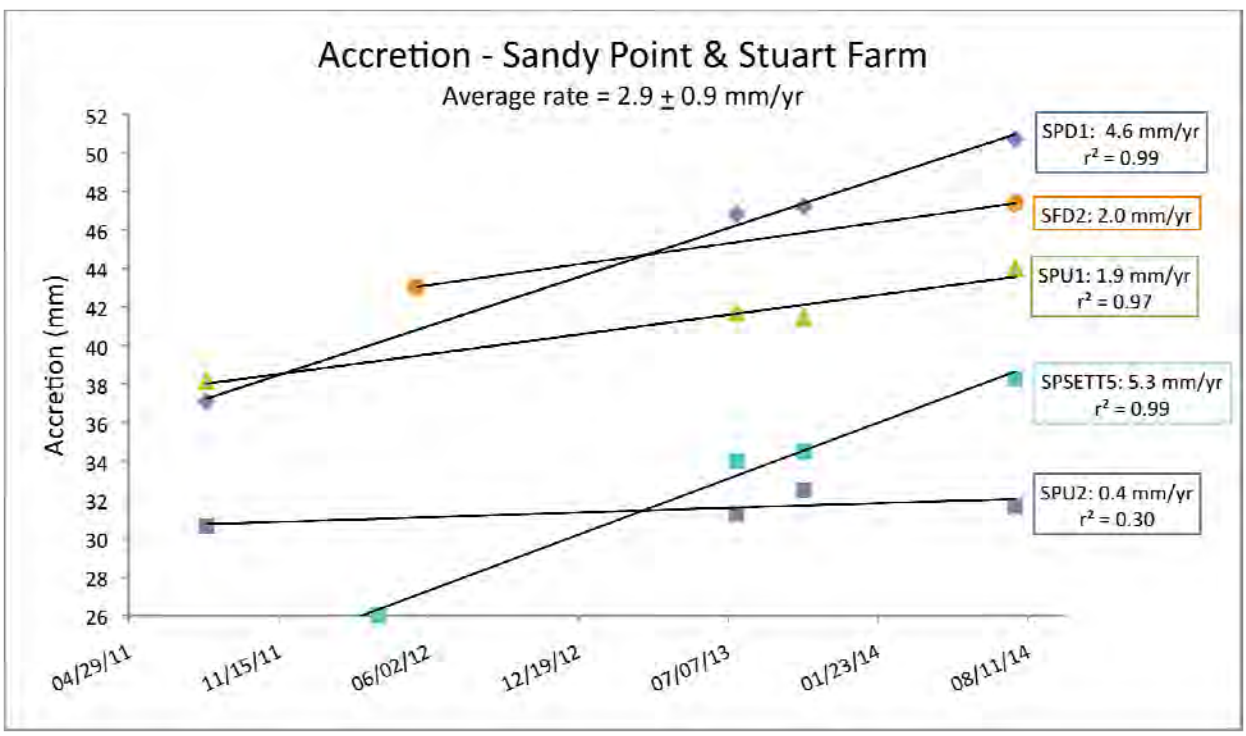

Figure 8. Sediment accretion over marker horizons for Sandy Point and Sturart Farm marshes in western Great Bay. Note SPSETT5 accretion levels were increased by 26mm and SPD1 and SFD2 decreased by 5mm and 15mm respectively, to facilitate visual comparisons.

Elevation and accretion rates near the coast at Awcomin Marsh varied considerably depending upon location and past restoration activities. For downstream SET stations (i.e., in undisturbed marsh), elevation increased at the highest rate in NH (4.4 ± 0.7 mm yr^{-1}), whereas SET stations upstream in a tidally impacted area (restored in 1992) were close to static: only 0.1 ± 0.6 mm yr^{-1} (Figure 9). Accretion at the downstream site (3.7 ± 0.4 mm yr^{-1}) averaged slightly higher than most NH sites, and accounted for approximately 80% of the total elevation change (Figure 10). On average, upstream SETs did not accrete in the past 3 years and instead eroded (-1.0 ± 2.8 mm yr^{-1}).

At Hampton-Seabrook Estuary where SET stations are much further separated than other marsh systems in NH, elevation and accretion rates showed little variability, averaging 2.1 ± 0.3 mm yr^{-1} and 2.8 ± 0.2 mm yr^{-1}, respectively (Figures 11 and 12). Accretion was greater than elevation change and thus accounted for all of the surface elevation gain. This also suggests peat below the marker horizon was decomposing and compacting faster than it was accumulating. Increases in elevation were consistent over time except from late Oct 2013 to May 2014, where the marsh surface at all six stations actually decreased by an average of 2.6 mm (Figure 11).

The elevation ranges of low and high marsh zones within HSE were compared to local tidal datums. On average, the intertidal marsh communities grew along an elevation range of 1.75 m (5.7 feet) from 0.37 to 2.12 NAVD88 m (Figure 13). The seaward edge of the low marsh was found to be 0.37 m (1.3 feet) higher than mean tide level (MTL). Low marsh extended up gradient by 0.80 m (2.7 feet) to the transition between low and high marsh, which occurred, just below mean high water (MHW). The average high marsh elevation occurred 0.10 m (4 inches) above MHW and high marsh extended 0.95 m (3.1 feet) to the upland edge, as indicated by an abrupt change in plant species.

Marsh zone elevations in HSE were further analyzed between the six sampling sites. Elevations were very similar for the transition from low to high marsh and the average high marsh elevation. However, the lower and upper edges of the marsh appeared to vary by sampling location (0.5 m range; Figure 14). R1 and 101, which are the two most northern sites in HSE, had the lowest low edge and lowest upland edge elevations (Figure 14). In contrast, WR and BS, located in the southern part of the Estuary, had the highest low and upland edges. Our results, analyzed as a regression of the low and upper edge ($p = 0.01$; r^2: 0.88), suggest the low and upland edges co-varied.

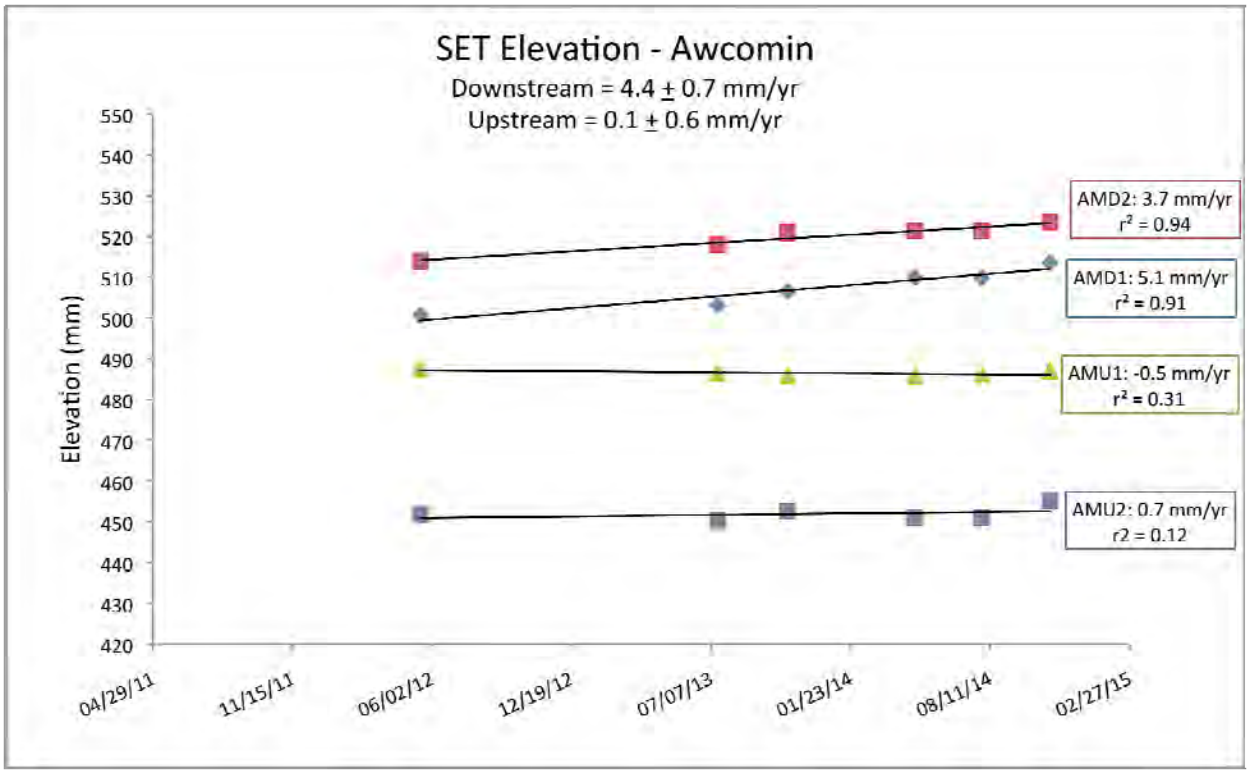

Figure 9. Changes to surface elevation for Awcomin Marsh at Rye Harbor.

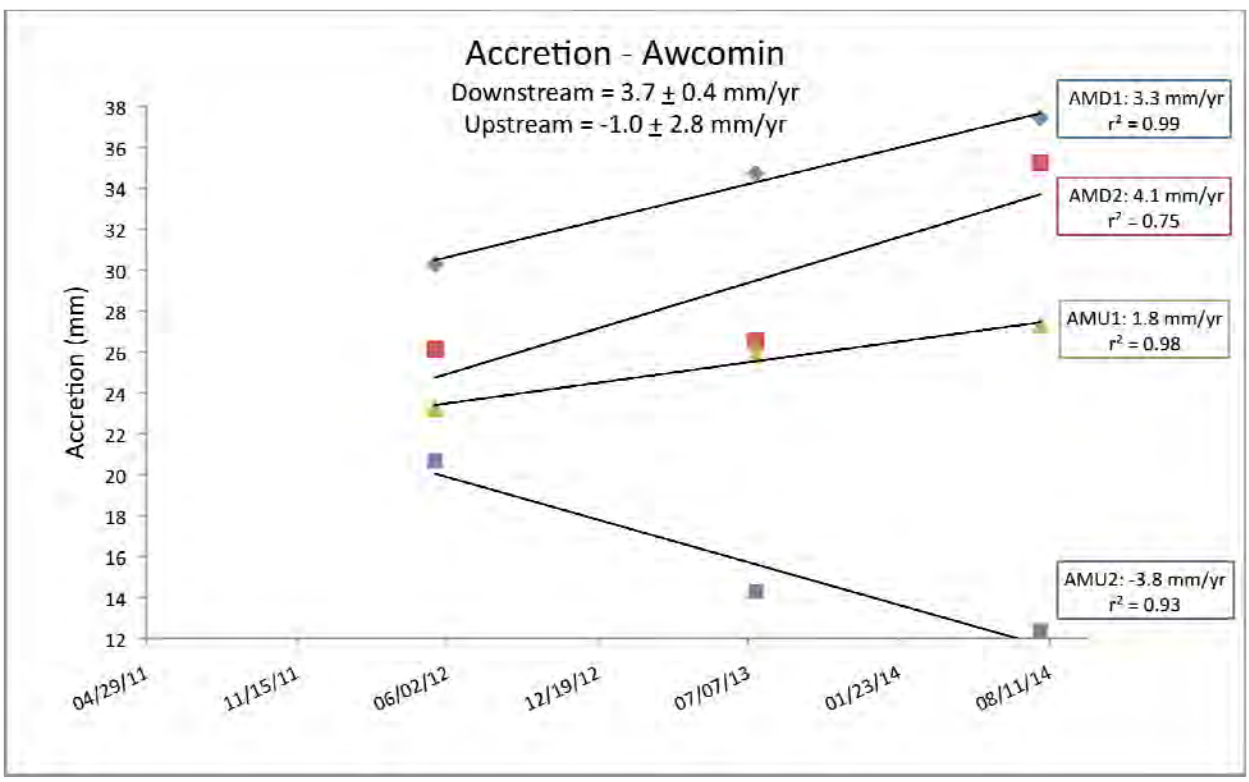

Figure 10. Sediment accretion over marker horizons for Awcomin Marshes at Rye Harbor. Note AMD2 accretion levels were decreased by 37mm to facilitate visual comparisons.

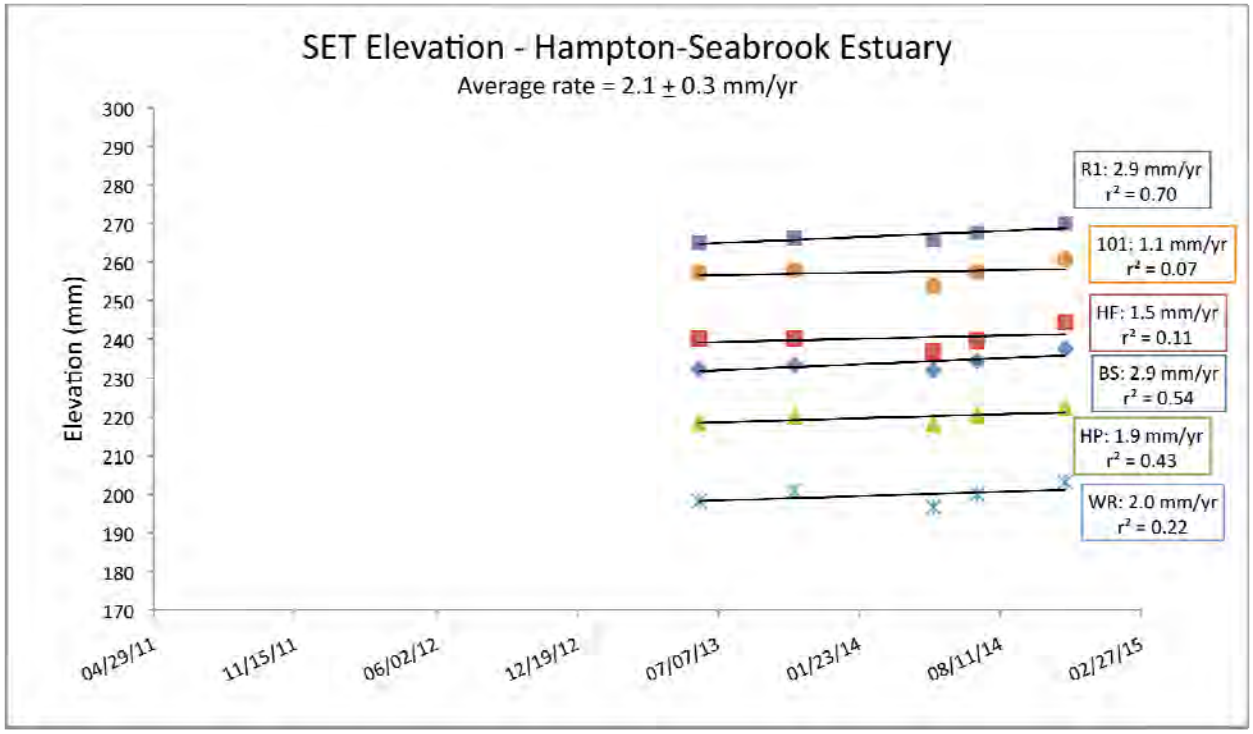

Figure 11. Changes to surface elevation for Hampton Seabrook Estuary.

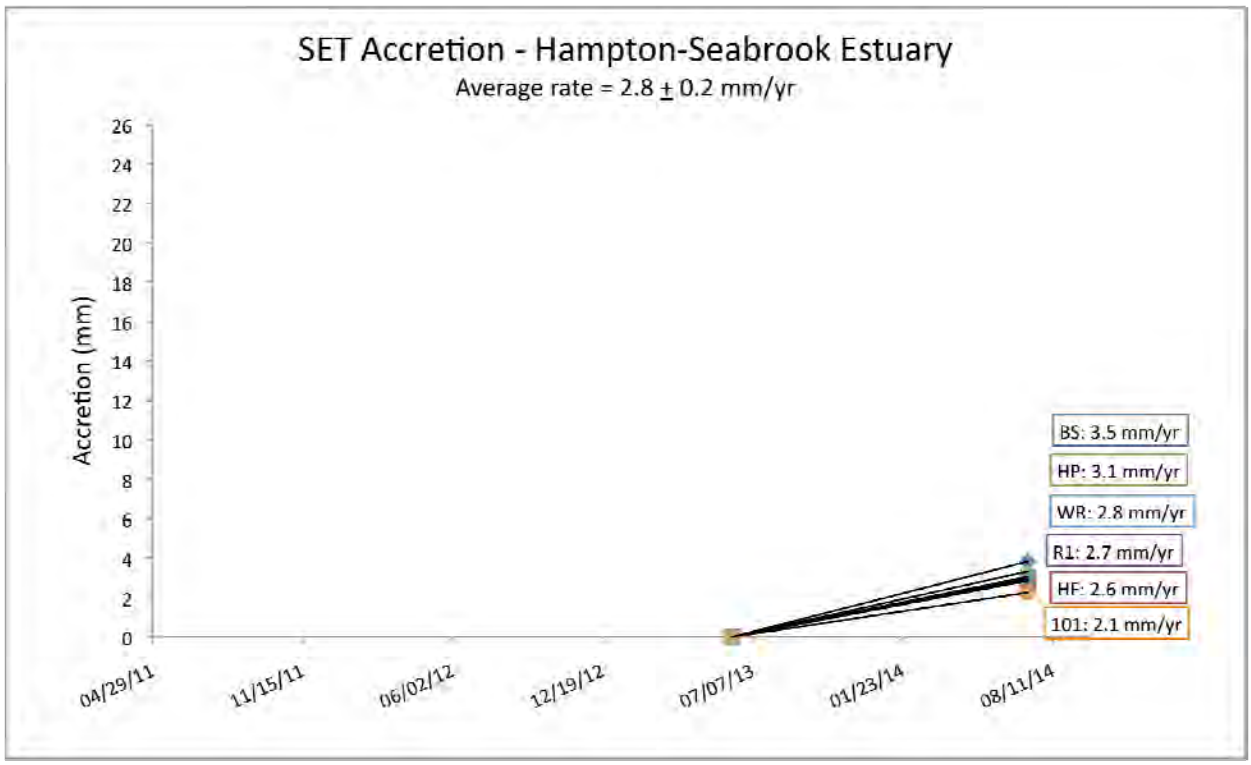

Figure 12. Sediment accretion over marker horizons for Hampton Seabrook Estuary.

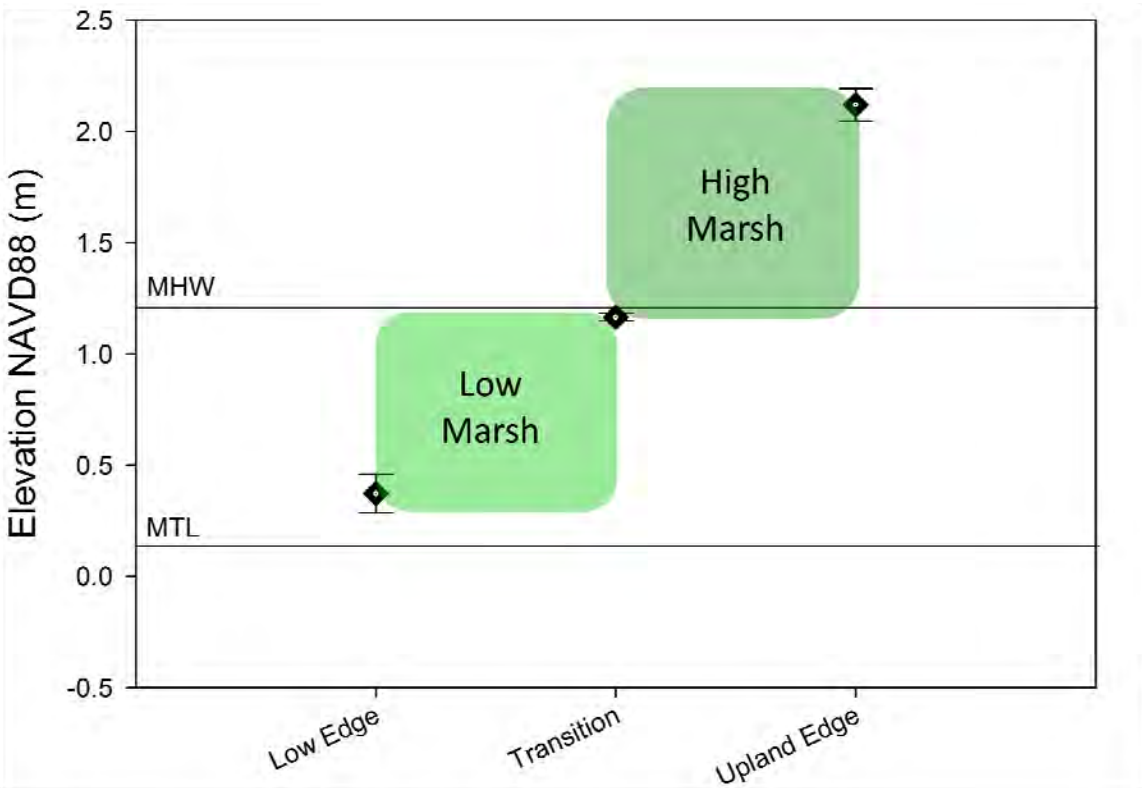

Figure 13. Average elevations of marsh boundaries, including low marsh lower edge and upper transition zone and high marsh transition zone (lower edge) and upper edge (at upland).

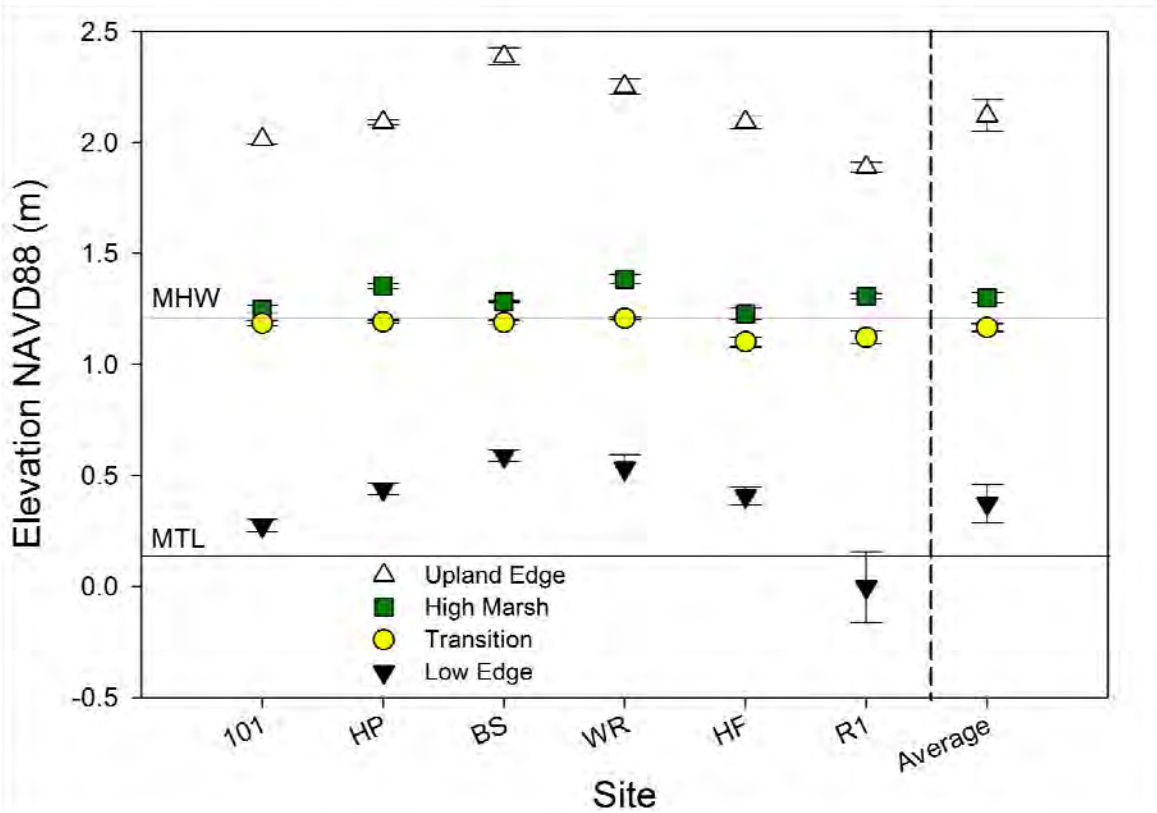

Figure 14. Elevation distribution of marshes at SET stations in the Hampton Seabrook Estuary.

Discussion

Over the past 3 years, the major marsh systems of New Hampshire have increased in surface elevation by 2.3 ± 0.7 mm yr^{-1}, and most all of this increase can be attributed to surface accretion. The rate of marsh building is slower than what we found from 2001 to 2010 in Great Bay and Webhannet estuaries, but similar to earlier rates at these sites (1995-2001; Stacey et al. 2012; Burdick et al. 2013). In contrast to the temporal variability in surface elevation, accretion rates appear to have little variation over time or among marsh systems. In New England, accretion rates were consistently between 2 to 3 mm yr^{-1} over the past 20 years, which is very similar to the rates found on average for NH over the past 3 years: 2.4 ± 0.9 mm yr^{-1}.

As pointed out earlier, accretion is a function of suspended sediments and marsh position in the landscape, neither of which are expected to change much over time. Processes leading to peat gains and losses, however, depend on plant production, sea levels, temperature, ice thickness and their interactions, which may produce variable results in peat accumulation. Building of elevation in New Hampshire marshes has appeared to slow in the past 3 years, which may be attributed to increases in compaction and decomposition processes. Our results show no elevation gain due to peat accumulation because on average, accretion was greater than total elevation gain by 0.1 mm yr^{-1} (Figure 4).

Although the response of marshes to sea level is not completely understood, the rapid period of marsh building (2001-2010) coincided with an unprecedented rise in sea level from 2009 and 2010 (Goddard et al. 2015). Subsequent to this rapid rise was a variable, but gentle drop in sea level for 2011 to 2013 (Figure 15). Such a period of lower sea level from 2011-2013 could have removed the advantage of peat gaining processes over peat loss processes and resulted in gains from only accretion, as observed in our study.

Increases in elevation for NH marsh systems were fairly consistent from 2011 to 2014, except during one time period, when the majority of SET stations decreased in elevation. From October 2013 to May 2014, half the stations at Awcomin and Great Bay Estuary along with all of the stations at Hampton-Seabrook Estuary decreased in elevation. This system-wide decrease in elevation may reflect seasonal changes. During the winter months in New England, snow and ice accumulate on the marsh surface, adding a massive weight that may temporarily compress the entire marsh platform. Experimental research that simulated ice compaction suggests the high marsh sediment surface can be compacted in the short term by ice (46 cm thick) up to 6.9 ± 0.7 mm (Argow & Fitzgerald 2006). In addition, they found as little as 10 cm of ice thickness could compact the surface of the marsh by 2 mm. Compaction from winter ice does not appear to have a lasting effect beyond several weeks. For our data, SETs were measured in the spring of 2014, right at the end of the ice

compaction period, only 2 to 4 weeks after snow and ice was removed from the marsh surface. Alternatively, the loss in elevation over the winter of 2013-2014 could also have been the result of peat decomposition due to warmer winter temperatures. Peat storage is dependent upon cold, anoxic conditions (cold and lack of oxygen reduces decomposition) and lower tidal levels or warmer temperatures could stimulate greater decomposition (Kirwan and Blum 2011). Regardless of the explanation for the elevation decrease measured just after winter, it appears that elevations had rebounded by the next measurement in summer for all stations.

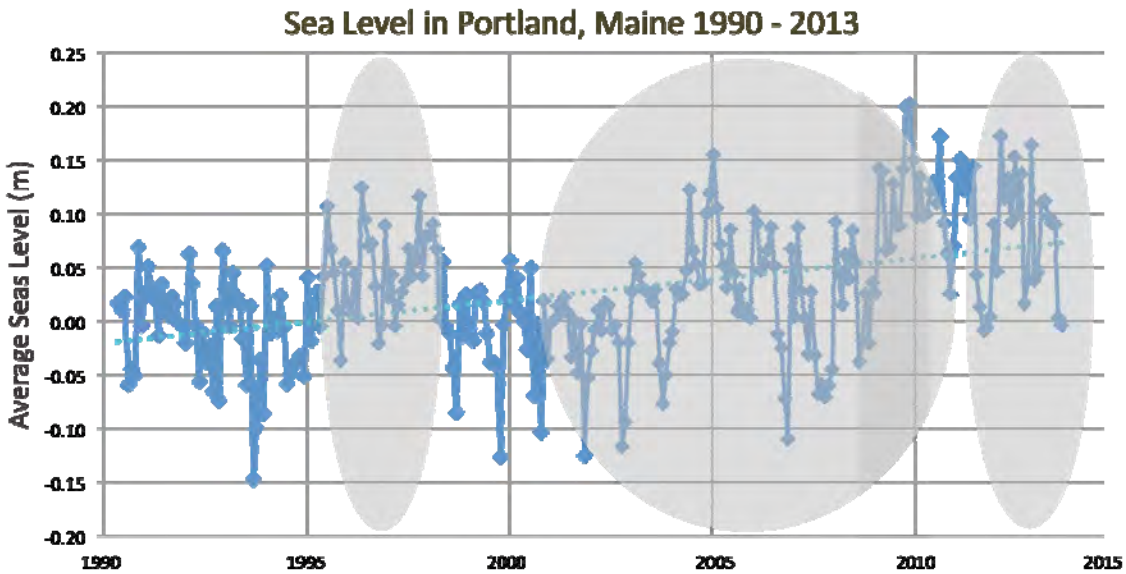

Figure 15. Monthly mean sea levels in Portland Maine. Note rapid rise in 2009-2010 (shaded rectangle) and periods of SET measurements for 1995-1997 with no sea level rise (shaded oval: Great Bay and Wells, Maine), a period of rapid sea level increase 2001 – 2011 (shaded oval: Great Bay and Wells Maine) and a period with no sea level rise 2011-2014 (shaded oval: Great Bay, Awcomin Marsh and Hampton Seabrook Estuary).

Tidal marshes in New Hampshire appear to build in elevation at similar rates (2 to 3 mm yr^{-1}), except for Awcomin Marsh, which deviated from this range at both downstream (4.4 ±0 .7 mm yr^{-1}) and upstream (0.1 ± 0.6 mm yr^{-1}). One reason why Awcomin differs from other New England SET rates may be due to its historic impacts and restoration activities. In 1941 and again in 1962, a large portion of Awcomin was filled with dredge spoils from the expansion of Rye Harbor that were contained by earthen berms (Burdick et al 1999). The expansion of the harbor also prompted engineers to relocate the tidal inlet to the marsh to accommodate the harbor and coastal roadway. Several decades later in 1992, partial restoration was achieved from the recreation of tidal creeks aimed to restore tidal flow into the area bermed and filled with dredge sediments. This highly impacted area, which is higher in elevation and remains tidally impaired, is where the Upstream SETs are located. In contrast, the downstream SETs are in a reference area next to a major tidal

creek, which is mostly un-impacted by human activities. We believe the multiple human impacts have prevented marsh building at the upstream sites (0.1 mm yr^{-1}).

The distribution of tidal marshes is tightly coupled to the elevation ranges over which they thrive, with the lower edge limited by flooding stress and the upper limit of dominance determined by competition with high marsh plants (Levine et al. 1998). A metadata analysis by McKee and Patrick (1988) examined the elevation range of low marsh where smooth cordgrass grew from Maine to Florida. They found the elevation range of low marsh varied due to tidal range, with the largest ranges at sites with the largest tidal range. With an average tidal range of 2.5 meters, HSE is at the upper end of the potential range and might be expected to to occur over a 1.5 meter range, but was only found to be dominant over ¾ of a meter; beginning 0.25 meters above the mean tide level (halfway between mean high and mean low tides) and extending almost to the mean high water mark.

The low edge of the low marsh and high edge of the high marsh were highest at the two southern sites, suggesting greater flooding in the southern relative to the northern portion of the estuary. It is not clear why the northern portion of the estuary would be flooded by tides to a lesser extent than the southern portion, but this result might be caused by wind stress, with strong northern winds reducing tides in the north and increasing tides in the south. In addition, the one site west of the rail road berm showed an appreciably lower edge to the low marsh as well as a slightly lower elevation for the change from high marsh to upland, indicting this site might experience less flooding than the other five SET locations in HSE. Less flooding at this site could be an indication of the rail bed posing a restriction to full tidal flow.

Conclusions

New Hampshire tidal marshes have been building at variable rates over the past two decades, which appears to be driven by regional fluctating sea levels. Earlier recorded rates of surface elevation change and sea levels in Portland, ME (Figure 15) were both low, then showed a period of rapid rise. The most recent measurement period, 2011-2014, showed slowing of marsh growth and little to no sea level change, suggesting a synchronization of marsh elelvation growth and sea level over the past twenty years. This appears to be more evidence for the positive feedback mechanism that allows tidal marshes to maintain themselves with gradual fluctuations in sea levels (Cahoon and Guntenspergen 2009, Burdick and Roman 2012). Additionally, our data indicate marshes

are able to cope with rapid increases in sea levels (Goddard et al. 2015) at least in the short term (1-3 years), by building at nearly twice their normal rate.

As communities plan for climate change and the increases in sea level predicted for our coasts, it will be valuable to also track the change in marsh elevation. Significant short term changes in sea level, such as that reported for 2009-2010 in New England waters, are slow to be recognized (Goddard et al. 2015) and used in planning, though still very useful. Our marsh data from 2011 told us that sea level was rising faster than any of the latest results available worldwide (Church and White 2011) or locally (Goddard et al. 2015), though we could not estimate how fast sea level was rising. Our marsh data collected as late as 2014 that are reported here show that sea level rise has abated for the present, with elevation increases fueled only by sediment accretion on the surface of the marsh.

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Appendices

See separate file