Long Term Reference Data in New Jersey Coastal Marshes: Perspectives on Elevation Dynamics and Thin Layer Placement

Special report

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The Partnership for the Delaware Estuary brings together people, businesses, and governments to restore and protect the Delaware River and Bay. We are the only organization that focuses on the entire environment affecting the river and bay — beginning at Trenton, including the greater Philadelphia metropolitan area, and ending in Cape May, New Jersey and Lewes, Delaware. We focus on science, encourage collaboration, and implement programs that help restore the natural vitality of the river and bay, benefiting the plants, wildlife, people, and businesses that rely on a healthy estuary.

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Introduction

Coastal wetlands, also called marshes, play a crucial role in the maintenance of clean waters. They are a hallmark feature of the United States' east coast and provide a variety of additional services to coastal communities such as flood abatement, wave attenuation, nutrient sequestration, and habitat enhancement. With human disturbance and the reductions in sediment supplies over past decades, coastal wetlands have been largely lost. Additionally, climate change and corresponding increases to rates of sea level are predicted to cause continued reductions in coastal wetland acreage and condition. There is potential to stem such losses with strategic planning and intervention using carefully designed restoration and enhancement projects.

Since Hurricane Sandy in 2012, interest in intervention strategies to ameliorate the degradation of coastal wetlands surged and tactics new to the state began to be investigated. Coastal wetlands are complex systems, however, and matching appropriate intervention tactics to site-specific vulnerabilities is challenging. The goals of this report are to:

- Supply practitioners with an understanding of marsh elevation, or platform, dynamics;
- Furnish examples of these dynamics in the Delaware and Barnegat Bay Estuaries using long term datasets; and
- Discuss the importance and utility of reference data from long term efforts to help improve intervention efforts.

What Governs Elevation Deficits?

The resilience of coastal tidal marshes to sea level rise is governed by dynamic processes that consist of several interconnected positive and negative feedbacks.[1-12] In the simplest sense, marsh elevation is controlled by sediment subsidies[13] and plant productivity, together maintaining the processes that allow the marsh to avoid drowning.[1-13] These two factors are usually co-dependent, where healthy sediment subsidies can yield high plant productivity and higher plant productivity enhances sediment capture.[13] The amount of sediment needed to sustain natural elevation maintenance and keep plants in their optimal growth ranges is site specific and relative to the energy of the system, tidal amplitude, rates of sea level rise, and sources of sediment.[2,6,7,8,9] Any alteration to the marsh's sediment subsidy and/or impacts to plant productivity would have consequences for resilience. Reduced **resilience** or poor **condition** (degradation) are not exclusive of the amount of sediment a marsh receives as there are many other factors that contribute to plant productivity.

Degradation of coastal wetlands typically coincides with increasing development of coastal areas. One of the many notable drivers of marsh degradation is decreases in sediment loads.[14] Sediment load reductions can be created by changes in land use, the construction of dams, or removal of the system's sediment subsidy* via dredging of navigational channels, such as in the Delaware River. Sedimentation, in addition to plant productivity, comprises net **surface accretion** which is a critical component of each marsh's natural ability to keep pace with rising sea levels.[6] Changes to the rate of surface accretion might influence the degree of impact that subsurface processes have on elevation maintenance (Figure 1) such that if **shallow subsidence** out-paces surface accretion, elevation is lost

*See the Delaware Estuary Regional Sediment Management Plan for more information: http://www.nj.gov/drbc/library/documents/RSMPaug2013final-report.pdf regardless of sea level. This process may take years to have discernible signs of degradation, but is expedited as sea level rises.[15] Additionally, degradation can also be caused by factors that affect the biological productivity of the system; a common such factor is eutrophication (i.e. high levels of nutrients, such as nitrogen or phosphorus).

Because marsh platform elevations are the result of several processes, many coastal researchers consider the marsh's absolute elevation, relative to rising sea levels and local tidal datums, to be an indicator of how vulnerable the system might be to climatic changes. This is referred to as the marsh's **elevation capital.**[15] A marsh with little elevation capital is likely to be the first to become overwhelmed with increasing tidal inundation as sea levels rise (Figure 2). Although low elevation capital is not a description of the true fate of the marsh, the likelihood of increasing vulnerability to degradation is higher for these marshes and so, it is these that are of the greatest management interest. Another consideration is that a marsh plagued with eutrophication may have adequate elevation capital, but may be undergoing decreases in below ground (root) productivity, which would diminish the biological contribution to elevation building over time. Surveys to discern elevation capital might be helpful to prioritize areas for management, but it is also necessary to assess other factors that contribute to degradation.[16] For this reason, a multi-metric approach is the most effective way to discern how marshes are impaired and what tactics are appropriate in ameliorating site specific stressors.

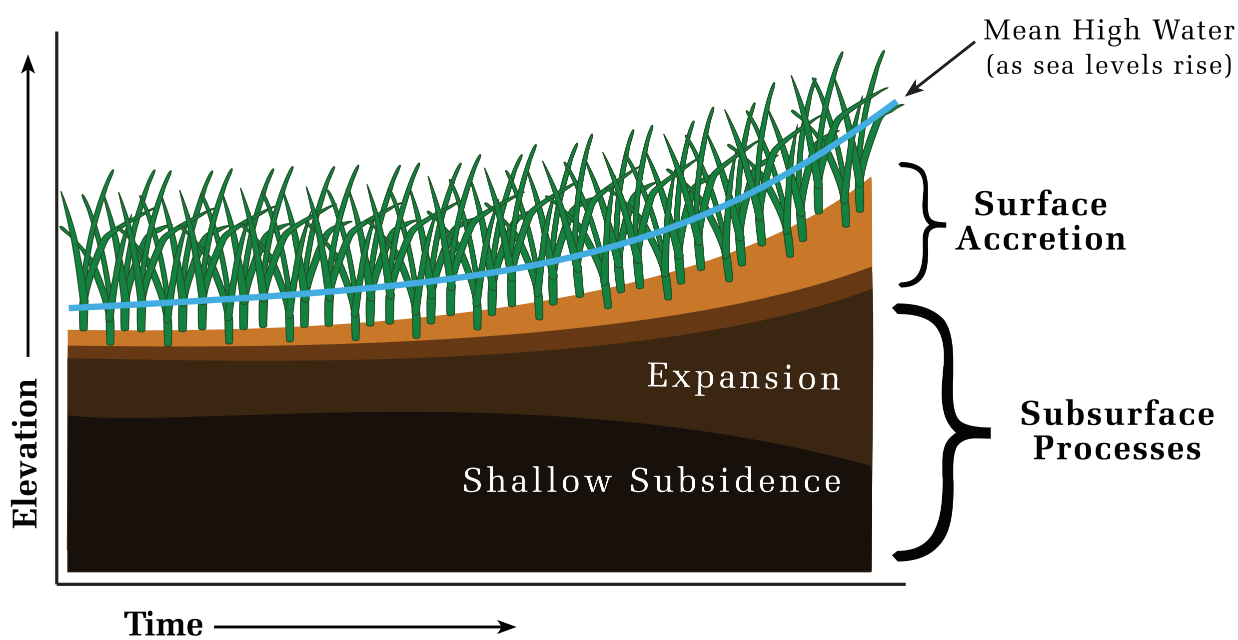

Figure 1. Surface processes which mediate elevation change in coastal marshes.

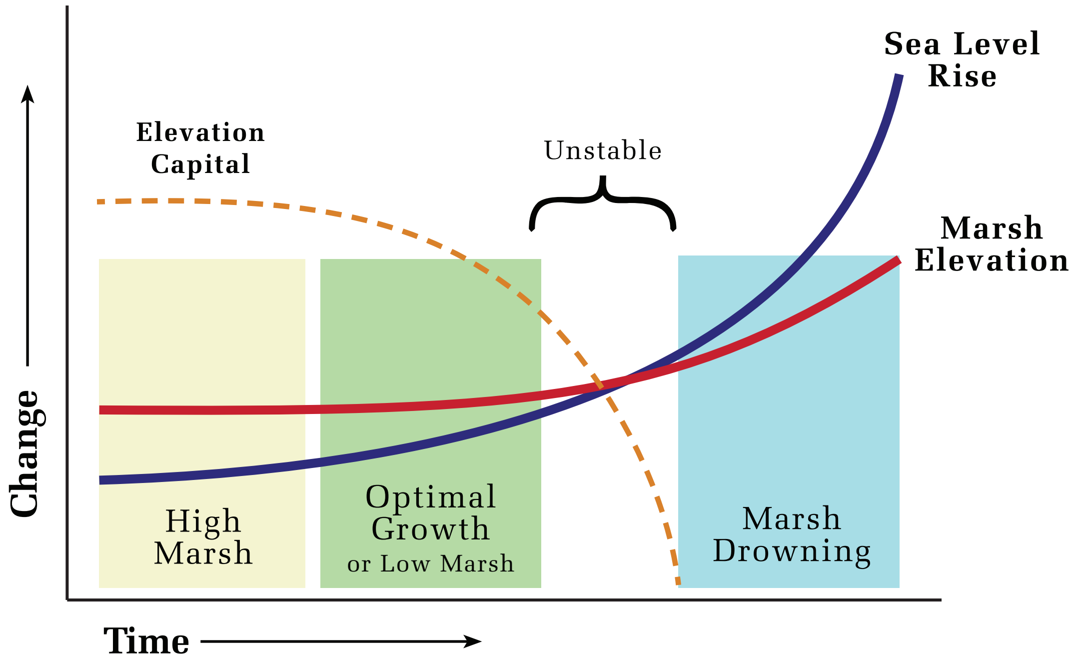

Figure 2. Relationships between sea level rise, marsh elevation, marsh productivity (i.e. growth or drowning), and elevation capital, as a high marsh site transitions to open water.[9,15]

Managing Net Surface Accretion

By carefully manipulating processes which affect net surface accretion or otherwise resolving specific problems negatively affecting a system, coastal managers and restoration professionals can prolong the time until a marsh drowns and enhance the systems' recovery response to detrimental episodic impacts, such as storms. In cases where marsh vulnerability to sea level rise is specifically linked to sediment or elevation deficits, restoration professionals may consider a variety of tactics designed to alleviate these shortfalls by managing the marsh's net surface accretion. The first step should be to examine whether the sediment deficit stems from some local management practice, such as a tidal restriction, that has been reducing the natural sediment supply. Tactics aimed at reversing sediment bottlenecks can then be prioritized to alleviate the underlying issue. Sediment capture may also be affected by unnatural energy and erosive forces such as boat wakes. In those cases, sedimentation might be enhanced by creating "no wake" zones or by constructing nearshore wave attenuation structures to create quiescent conditions more conducive to sediment capture.

In cases where marshes have insufficient sediment supply and there are no options for enhancing natural sediment supply, ameliorating external sedimentation stressors are not possible, active sediment placement can be used to adjust elevation shortfalls internally. Sediment placements can be sourced from dredged materials and are sprayed as a slurry across the marsh platform, a technique which has been used for more than 40 years. Also known as **beneficial use/reuse** or **thin layer placement** (TLP), this practice has shown success in ameliorating signs of degradation due to insufficient sediment loads or rapid shallow subsidence in marshes along the Gulf and southeastern Atlantic coasts.[17-23] This is a direct intervention tactic, which requires an understanding of the processes being manipulated by its deployment (Figure 3). Even when done correctly, this tactic also does not resolve all

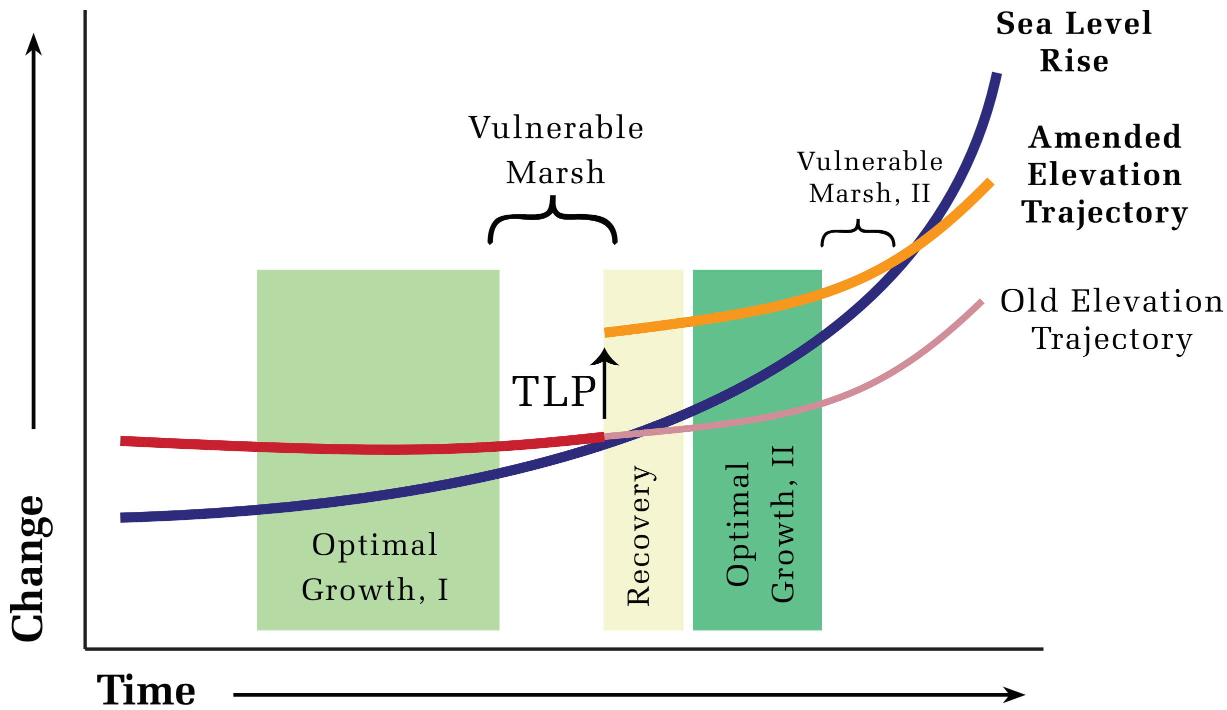

Figure 3. Theoretical effect of Thin Layer Placement on the relationships between sea level rise, marsh elevation, and marsh productivity (growth) for a particular coastal marsh tract threatened with drowning.

of the underlying problems which might cause elevation deficits or reduced sediment subsidies (i.e. land use, dams, tidal restrictions, deep subsidence), so TLP may only decrease vulnerabilities over abbreviated periods of time.[16,22] Much like beach sand replenishment, repeated applications onto sediment starved marshes might be justified by the return on investment (ROI) from sustained ecosystem services. Long term monitoring of these projects is essential to understand the need for future interventions and to quantify the enhancement of marsh resiliency by these practices.[24,25]

Previous TLP Studies

Since the 1970-80's hydraulic dredging has become more affordable, making the deposition of clean dredged materials onto marsh surfaces a feasible restoration tactic. The technique is well known in the south, particularly in Louisiana,[26] where rates of subsidence are nearly 7 times greater than that of New Jersey (~7 $mm \cdot yr^{-1}$ in LA versus 1.2 $mm \cdot yr^{-1}$ in NJ).[27,28] A variety of studies have shown that various depths and types of sediment placement can have beneficial effects on a deteriorating marsh.[17-23,29-31]

Although the TLP technique has been applied successfully, there are several cautionary items that must be addressed. In 1978, Reimold et al.[21] studied the potential smothering effects of TLP, using different sediment grain sizes and placement depths. One important findings of their study was that vegetative regrowth of smooth cordgrass *(Spartina alterniflora)* rhizomes occurred when placement was much less than 61 cm (24 in). Other successful projects also had placements depths less than this threshold.[19,23,29,30] Wilber and Engler[22] suggested that studies from Louisiana and North Carolina had success with sediment placements between 5-15 cm (2-6 in). They also suggested that sediment placement that is too deep for adventitious rhizome regrowth will depend on seedling survivorship for recolonization, a process that can take years to achieve desired results.

Target placement depth may also be very different from targeted elevations. Sediment slurries can contain up to 80% water, which will dissipate from placed sediments and factors such as compaction, migration, and episodic storms may play a part in placed sediment adjustments over time.[18,23] From data collected by Reimold et al.,[21] Wilber and Engler[22] found that placement depths generally decreased by 10-40% depending on initial thickness, such that post-consolidation thicknesses of 5-15 cm (2-6 in) may have had an initial placement depth of 8-45 cm (8-18 in). Anticipating the initial dewatering and compaction processes of placed sediments is key to creating long term localized elevation targets. It is extremely important that placed sediment targets be accurately achieved to avoid too much or too little elevation adjustments. The danger of underestimating placement depths may result in resiliency goals not being met and shortened time frames of re-application, if necessary. Conversely, overestimating placement depths poses the risk of elevating the marsh platform above tidal influence. More studies need to be carried out on post-consolidation processes in New Jersey marshes to help guide expectations on final placement results.

As previously mentioned, marsh platform elevations are controlled by a suite of processes, so the addition of placed sediment should only be used to bring marsh up to a desirable elevation without negatively impacting these dynamics. Too much elevation gain from sediment placement could act as marsh fill, elevating it to the point of little or no regular tidal inundation or inducing a tipping point that converts the marsh into mudflat; too little might not have the desirable restorative effects. Wilber and Engler[22] state that elevations from adjacent marshes should be used to help identify post-consolidation elevation targets. Placement depths should be set to reflect deficits in elevation at specific tracts of marsh using surrounding, healthy marsh as frames of reference. It is just as important to identify short and long term adjustments to platform elevation caused by TLP, as it is to match the desired or targeted ecological outcome to local conditions. Previous studies or reviews are crucial for understanding previously identified ecological constraints, but the final TLP depths and desired outcomes are largely dependent on several site specific factors, including the surrounding marsh condition, vegetation types, intervention goals, and project time lines.

Reference Data

Reference Data and Resources

Generally, budgets for intervention projects are limited, and so it is critical to choose the most efficient and cost-effective methodologies to enhance coastal wetlands to maximize success and return on investment. Selection of appropriate tactics can be enhanced by completion of surveys of marsh condition to gauge relative vulnerabilities and match these to appropriate intervention tactics. There are many techniques on which to gauge condition and vulnerability but core themes include:

- Mathematical modeling of the marsh surface and hydrology;[31]
- An understanding of ecological constraints on the system;
- Field assessments of current marsh condition;[24] and
- Identification of restoration goals and targets for various scenarios of sea level rise.

Long term monitoring plans that include control and reference datasets are also needed to unequivocally judge project success, failure, and how to improve techniques. A science based approach contrast outcomes with "no action" alternatives, represented by untreated controls near the project site. Additionally, the use of reference data in tandem with control data is beneficial, as it aids in understanding broader coastal marsh processes. In the Delaware and Barnegat Bay Estuaries, some reference data can be obtained through the Mid Atlantic Coastal Wetland Assessment (MACWA). These data are part of ongoing studies of coastal wetland function and condition in the Mid Atlantic region. These studies provide managers and practitioners with information on spatial and temporal trends of coastal wetlands, including stressor-response relationship and vulnerabilities that vary widely from place to place.

Mid Atlantic Coastal Wetland Assessment

The Mid Atlantic Coastal Wetland Assessment[25] (MACWA) is operated by the Partnership for the Delaware Estuary, the Barnegat Bay Partnership, and the Academy of Natural Sciences of Drexel University. MACWA is supported, cited, and used by a network of coastal wetland science professionals from New York to Maryland. Besides providing an understanding of spatial and temporal status and trends of coastal wetland health and extent, MACWA datasets provide information on elevation and accretion dynamics for coastal marshes of New Jersey. Therefore, these data can help set regionally and locally appropriate restoration or intervention targets, such as those that would yield greatest vegetation robustness from TLP.

MACWA is a comprehensive multi-tiered wetland assessment program extending from regional census datasets to local intensive analyses (Figure 4). Each

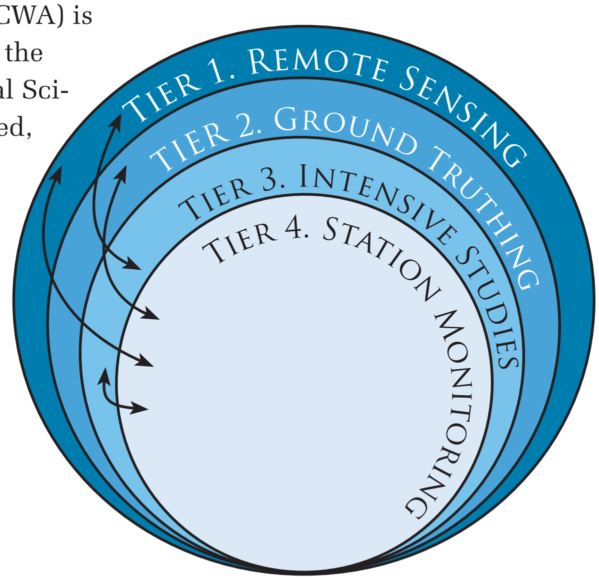

Figure 4. Four cross linking tiers of the Mid Atlantic Coastal Wetland Assessment program.

MACWA tier contributes vital information on wetland condition and related processes, but at different temporal and spatial scales. Tiers were designed to be cross linked to create a robust and thorough assessment. Data presented here were collected through Tier 4: **Site Specific Intensive Monitoring** (SSIM). SSIM is the MACWA program's long term monitoring effort at fixed sentinel sites. SSIM consists of a suite of metrics including water and soil quality; plant distribution and biomass; and long term elevation dynamics.

To demonstrate how core MACWA SSIM metrics help identify where TLP might be useful, and to help set targets for TLP sites, in this report we furnish and interpret data from the following metrics: Surface Elevation Table (SETs), Marker Horizon (MH), and Real Time Kinematic GPS surveys. These data provide a basis for:

- Understanding elevation processes that could be manipulated using TLP;
- Provide *a priori* knowledge on which areas might benefit or be harmed by placing sediment.

Methods

SSIM Station Layout

There are currently six mature (>3 years) SSIM stations located in New Jersey salt marshes, but as of 2016, the SSIM program in its entirety sustained 11 stations in New Jersey, Delaware, and Pennsylvania. Three of the New Jersey stations are located along the Bayshore in the Delaware Estuary (west to east: Dividing Creek, Maurice River, and Dennis Creek) and three are in the Barnegat Bay Estuary (north to south: Reedy Creek, Island Beach, and West Creek)(Figure 5). All stations are dominated by typical salt marsh grasses: smooth cordgrass (*Spartina alterniflora*), salt hay (*Spartina patens*), and salt marsh grass (*Distichlis spicata*). The Delaware Estuary stations have salinities ~15 ppt, with tidal amplitudes of approximately 1.8 m (6 ft). Barnegat Bay, a shallow lagoon, is more saline (~20 ppt) and has smaller tidal amplitudes (0.1-0.6 m; 0.3-2 ft) than the Delaware Bay.

Each SSIM station was designed to include three surface elevation tables, each with three marker horizons (see below; for other layout descriptions, see Appendix A). Metrics such as biomass, water quality, and soil quality samples are collected annually in the vicinity. Annual non-destructive vegetation monitoring is also completed. Both grid and transect style real time kinematic (RTK) GPS elevation surveys (vertical accuracy is <±6 cm, or ~2 in) are completed every 1-3 years. Although all metrics are collected routinely, the focus of this report is on elevation dynamics. The remaining metrics will be the subject of future reports but are generally available upon request.

Surface Elevation Tables

Each SSIM station has three deep rod surface elevation tables (SET) and nine feldspar marker horizons (MH)(Figures 6 and 7), which were installed and continue to be read as described in the works of Donald Cahoon (USGS), James Lynch (NPS), and Philippe Hensel (NOAA), among others.[32-36] An in depth review of methodologies and theories of SET-MHs can be found on the USGS Patuxent Wildlife Research Center's website (https://www.pwrc.usgs.gov/set/).

Surface Elevation Tables track cumulative elevation changes and corresponding marker horizons

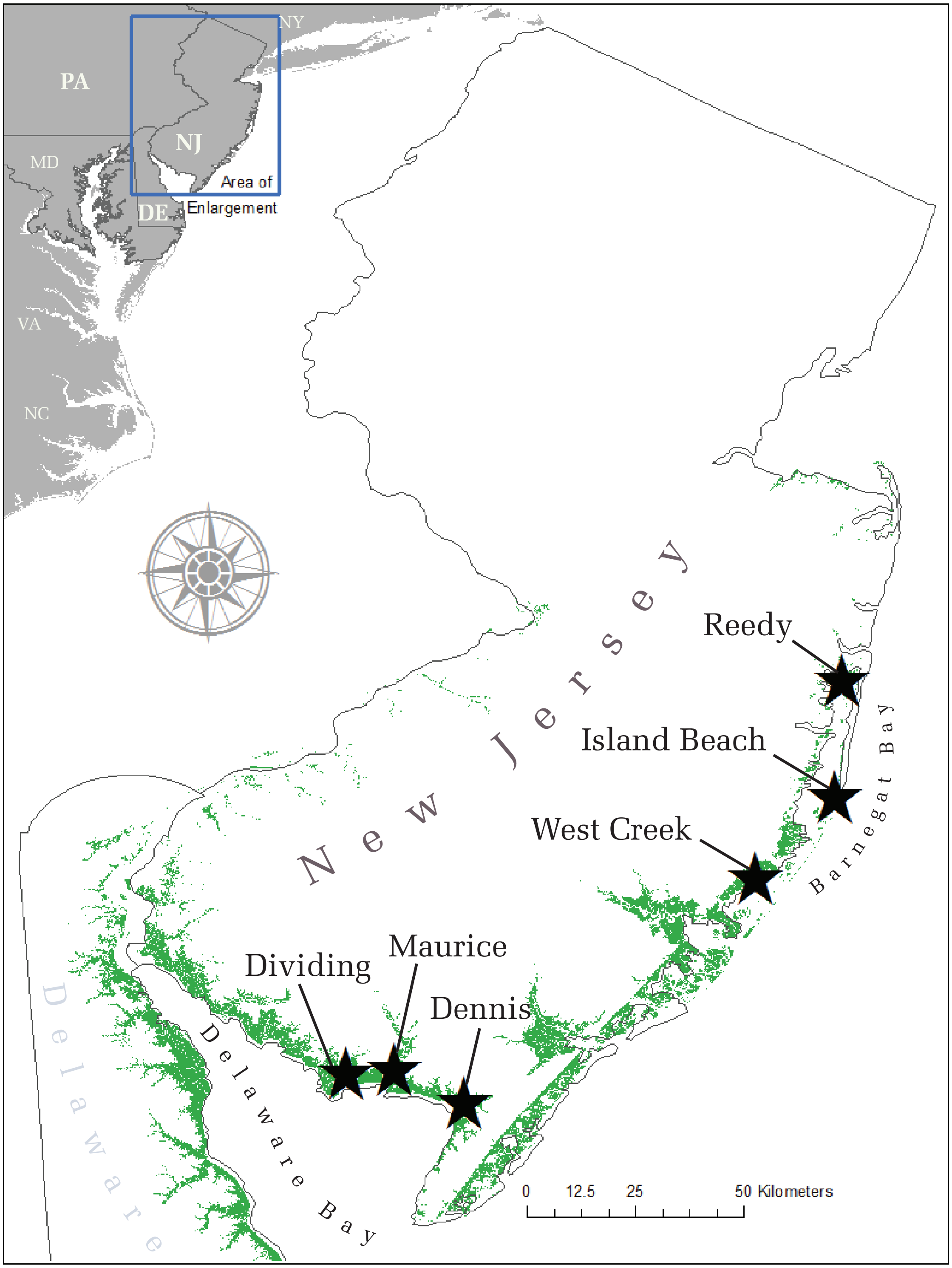

Figure 5. Site Specific Intensive Monitoring stations within New Jersey salt marshes. All tidal wetlands, based on National Wetlands Inventory (https://www.fws.gov/Wetlands/nwi/) data, are in green.

are used to monitor short term accretion on the marsh platform. Shallow subsidence (SS) is the reduction in elevation, or sinking, of the wetland surface between the bottom of the SET benchmark and the bottom of the marker horizon. Subsidence dynamics are controlled by subsurface processes and hydrology. SS is equivalent to the difference between cumulative elevation change and the rate of accretion (see Figure 6 and 7).[36] A marsh platform is considered to be "keeping pace," or vertically stable, when the cumulative elevation change is greater than or equal to the local rate of sea level rise.

All rates of sea level rise referred to in this report are from NOAA's sea level rise trends (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html): Cape May (ID 8536110) for the Delaware Estuary (4.54±0.55 mm·yr^{-1} or ~ 0.015 ft·yr^{-1}) and Atlantic City (ID 8534720) for Barnegat Bay (4.07±0.16 mm·yr^{-1} or ~ 0.013 ft·yr^{-1}).

Data derived from SETs and MHs were analyzed from installation (~2010) to the most recent date available, generally autumn 2015, using linear models in R Statistical Software.[37] Linear model formulae (y=mx +b) were used to calculate the number of years it would take to naturally accrete 18 cm (7 in) under current rates. Anecdotal placement depths for potential and existing TLP projects in New Jersey have been from 2 inches up to 2.5 feet; to provide a basis for comparison, a median value of ~7 inches (18 cm) was chosen.

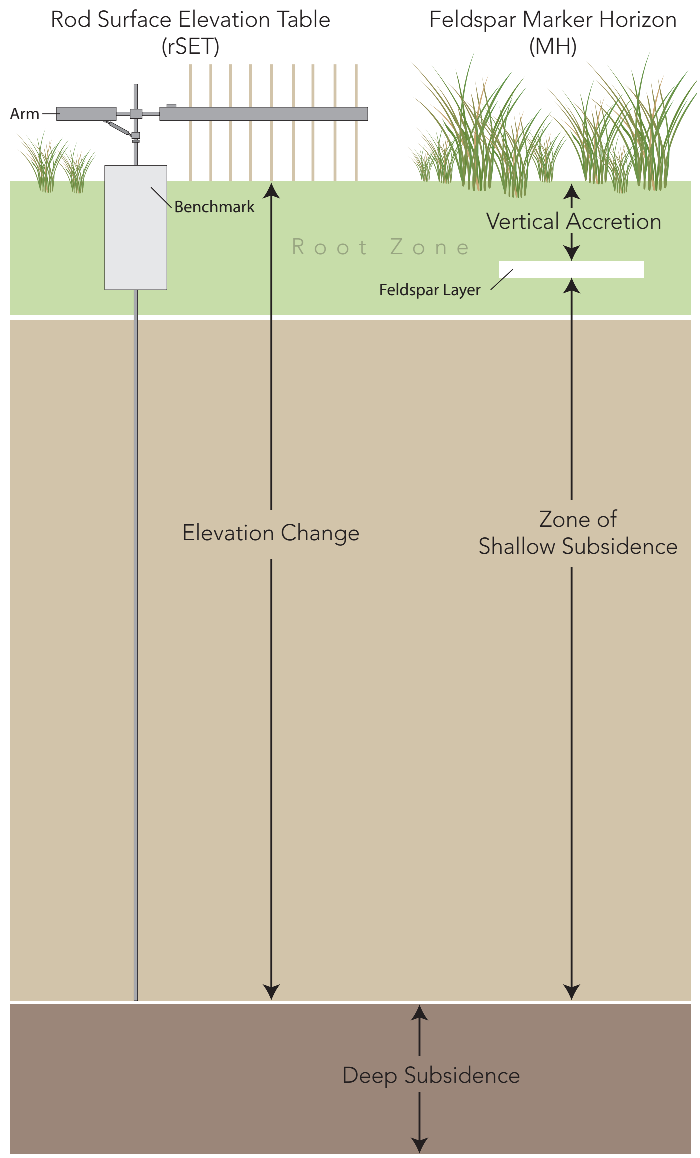

Figure 6. Theory of a surface elevation table and marker horizon (SET-MH). Track elevation change and short term vertical accretion, respectively. Diagram was adapted from the original by Don Cahoon at USGS Patuxent Wildlife Research Center.

Linear models were used to estimate accretion depth given an additional five years (i.e. ~10 year period from installation to the end of the extrapolation period). They were also used to estimate elevation adjustments (e.g. deficit) a marsh platform would accrue in the same time frame by accounting for local rates of sea level rise[38] (Table 4). Platform elevation changes in response to sea level rise are non-linear processes, especially over long periods of time.[9,39,40] Because these datasets are relatively short (<6 years), linear models are still the best statistical fit. As more data are collected, non-linearity should be more detectable. It should be noted that these values may underestimate biogeomorphic responses to accelerating sea levels, and therefore should only be used to gauge the ecological con-

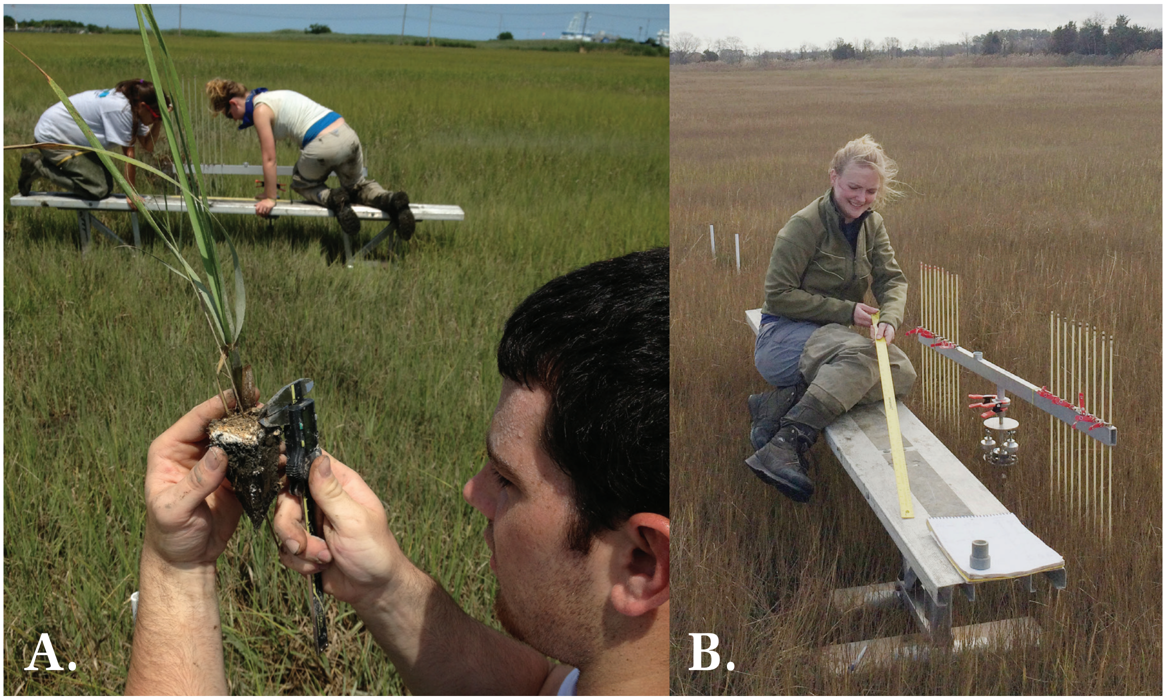

Figure 7. Measuring accretion, or the material above the feldspar layer in a salt marsh system (A) and measuring cumulative elevation change using a surface elevation table (B). Photos taken by PDE staff.

straints of a system to help set TLP targets for the near future (within 2-3 years of the release of this report). SET-MH trends will continue to be reanalyzed with new data, as it is collected.

Elevation dynamics are very site specific and it is not appropriate to extrapolate these data to tracts of marsh larger than the footprint of the SET-MH (e.g. >10 m dia.). They are, however, representative of the variability in elevation dynamics in the vicinity of the SSIM station and provide a useful frame of reference for understanding the natural dynamics which might be observed at a particular location. Perspectives to be gained from SET-MHs may include, but are not limited to: determining if there are deficits in accretion and understanding the role of shallow subsidence on elevation change.

Elevation Data

Elevation data collected using RTK GPS were also collected by surveying the marsh platform in the immediate vicinity of each of the six SSIM stations. Such surveys take two forms: transect (limited to representative linear surveys through zonation) and grids (more extensive). Currently, only 3 of the 6 sites have grid data, but all sites have transect data. Only vegetated survey points were used in this report in order to understand the distribution of elevations in which vegetation occurs. A majority of the surveying was conducted in high marsh areas. Elevations were summarized by violin plots in the Ggplot package in R.

Data derived from Morris et al.[9] were used to calculate optimal plant growth elevations (OPGE). This was done by calculating the optimal distance from mean high water (MHW) as a ratio from the Morris et al. study location (North Inlet, South Carolina), assuming that plant growth responses to inundation would be similar from South Carolina to New Jersey. This adjustment takes into account the differences in the size of each SSIM station's tidal prism (for more information about the variation in tidal prism size among all New Jersey's coastal areas, see Appendix B). For example, the median distance below MHW which Morris et al. deemed optimal was 50±10 cm, for a location where the tidal prism was 1.43 m (or ~35%); this was equal to 61±12 cm below MHW at Maurice, as the tidal prism is 1.75 m or 3.7±1 cm at Island Beach, where the tidal prism is 11 cm. These ranges where subtracted from the local MHW, as derived from NOAA's VDatum* tool. These datum and ranges were then graphed with elevation violin plots.

Of note is that Morris et al.'s work on OPGE was carried out for above ground biomass, and is most representative of low marshes dominated by *Spartina alterniflora*. High marsh OPGE is likely ≥MHW (e.g. mean higher high water, MHHW); consists of a mix of species (e.g. *Spartina alterniflora, S. patens,* and *D. spicata)*; has more productivity in below ground biomass; and, since surficial flooding is infrequent, production is likely more affected by groundwater dynamics. Therefore, in high marshes, below ground production is likely larger with respect to above ground production compared to low marshes. The specific data required to calculate OPGE for high marshes does not yet exist for New Jersey.

Reimold's Smothering Depth

Reimold et al.[21] surmised that at St. Simon's Sound, Georgia, the smothering depth of *Spartina alterniflora* was between 30-61 cm. The size of the tidal prism (MHW-MLW), as derived from the St. Simon's NOAA tidal datum station is 2.018 m (201.8 cm). No studies exist on whether $D_{smother}$ is an empirical characteristic of *S. alterniflora*, but since marsh plant productivity is largely influenced by inundation of tidal water, $D_{smother}$ was considered to be proportionate to the size of the local tidal prism. Similar to the methods described above for OPGE given local tidal datum, and assuming plant growth responses are similar in New Jersey, smothering depths ($D_{smother}$) were calculated for each SSIM station given a 45.5 cm mean smothering depth at St. Simons.

Reference vs. Control Data

Reference data, in the context of this report, are not equivalent to study controls, which compare the direct effects of intervention. Reference data are used to: 1) cite local elevation dynamics or ecological relationships when designing a project; 2) better understand marsh responses to stressors (e.g nutrients, episodic storm events); 3) provide local examples of long term trends; 4) create or set attainable restoration goals that are relative and specific to the target area; 5) test the validity of control sites based on responses observed regionally; and 6) compare project success to marshes of known conditions (or health). Reference data are therefore useful for understanding broad vulnerability patterns that can guide restoration project types and design locations, as well as provide a frame of reference for monitoring project outcomes. The utility of study controls are limited to project performance assessment and monitoring by contrasting results from treated and untreated alternatives.

Here we provide an example of data on OPGE and surface elevation dynamics can be used as reference data to guide TLP project decisions in reasonable proximity to a SSIM station. Reasonable proximity can be variable, depending on the inherent variability of the system of interest, but is more or less within 1 or 2 HUC 12s. Tidal prisms should vary from reference location to project site by less than 30 cm when amplitudes are >1.5 m, or less if amplitudes are <1.0 m. These suggestions are general, and further studies on system variability would be needed to craft more specific guidelines.

*https://vdatum.noaa.gov/vdatumweb/vdatumweb?a=113602620170215

Results and Discussion

Surface elevation table (SET) and marker horizon (MH) data, as analyzed using linear models, are summarized in Tables 1 and 2, respectively, for the 6 New Jersey SSIM stations. More than half of SETs studied (10 out of 18) from 2010-2015 did not keep pace with local sea level (~4.5 mm·yr^{-1} for the Delaware Estuary or ~4 mm·yr^{-1} for Barnegat Bay)(Table 1). At no station did all three SETs have elevation changes greater than sea level rise. At Island Beach, all three SETs experienced negative cumulative elevation change. Accretion rates were variable among stations and estuaries (Table 2). Hense most of these reference stations appear to be losing elevation capitol.

To better understand the contribution of accretion rate to elevation maintenance, shallow subsidence rates were calculated. In Table 3, shallow subsidence and the amount of material accumulated since installation is summarized for each SET-MH. When shallow subsidence is greater than accretion, elevation is lost due to surface accretion deficits. Five of the SETs analyzed, however, experienced subsurface expansion (negative rates of shallow subsidence), which suggests that below ground production may contribute to elevation maintenance. Subsurface expansion was more prevalent in Barnegat Bay (4 of 9 SET-MHs) than in the Delaware Bay (1 of 9 SET-MHs).

Assuming recent trends will continue, it is informative to project short term future trends. Estimates of the years to reach 18 cm of accretion, 5 year future estimates of accretion, and platform elevation deficits with respect to SLR rates are in Table 4. Time-frames for the accretion of 18 cm of material ranged from 12.9 to 48.9 years in the Delaware Estuary. In Barnegat Bay, Reedy and West Creek, this range was 3.67-64.2 years. Island Beach had very little accretion and SET 1 experienced surface erosion. Island Beach is undergoing pond formation and expansion between old mosquito ditches. The ponding processes led to an estimated -211 years to accrete 18 cm at SET 1; or as can be better described, 211 years of surface erosion is 18 cm of materials lost. These "year-to-accrete" values provide a reference for discerning how much of an impact sediment placement might have on these marshes given their natural rates of accretion. Longer time frames (e.g. >50 years) suggest that 18 cm is disproportionately larger than what the station is currently experiencing naturally. In many cases, natural elevation changes are not adequate to keep pace with sea level, but avoiding negative impacts to natural elevation dynamics by adding too much material is crucial to long term intervention success. Adding 18 cm of material to marshes within the Delaware Estuary is comparable to less than 50 years of natural accretion, and sometimes less than 2 decades, but in the Barnegat Bay, 18 cm might comparable to decades to even centuries of natural accretion (e.g Island Beach). Therefore, avoiding adding too much sediment (ie. via TLP) is particularly important in the Barnegat Bay.

Calculating the smothering depth ($D_{smother}$) is useful as a guide for "do not exceed" TLP depths. The goal in determining targets should be to promote adventitious growth by *S. alterniflora* (Table 4). The years to accrete 18 cm provide insight for geomorphic (elevation) functions, likewise $D_{smother}$ offers perspective for biological functions. Both functional metrics (i.e. geomorphological and biological) should be considered when designing placement depths. A depth of 18 cm of material is below the estimated $D_{smother}$ of *S.alterniflora* within the Delaware Estuary by about half, so geomorphic functions will likely be negatively impacted before biological thresholds are reached. In contrast, $D_{smother}$ depths in Barnegat Bay were below an 18 cm placement by approximately 4-15 cm suggesting biological functions will be negatively impacted as placement depths reach 2.5-13.5 cm.

Although elevation dynamics (i.e. SET-MHs rates) are important for determining vertical stability, elevation capital and elevation distributions (i.e. absolute elevations from RTK surveys) should also be considered for assessing spatial vulnerabilities to sea level rise. Violin plots of elevation data from RTK GPS surveys, tidal datum ranges, and calculated low marsh growth ranges are in Figure 8 (see Appendix C for raw values). Violin plots are similar to box-whisker plots, but incorporate a kernal density calculation so that the abundance of data points along the quantitative axis (y-axis) can be visualized. The wider the violin plot, the higher the relative density of data points. On average, the modal platform elevations were approximately ~0.18, ~0.125, and ~0.4 m NAVD88 for Island Beach, Reedy, and West Creek, respectively. In the Delaware Estuary, modal platform elevations were ~0.62/0.87 (bimodal), ~0.87, ~0.62 m NAVD88 for Dennis, Dividing, and Maurice, respectively. These elevations can be used to compare whether marshes of interest are lower or higher in elevation. If lower in elevation, these data can then be used to establish benchmarks for post placement elevation target ranges, as well as a prior development of "do not exceed" depths, after site specific elevation distributions are thoroughly surveyed.

Violin plots also show the distribution of elevations above MHW (white envelopes extending above light green bars in Figure 8), as most stations had a high abundance of points in high marsh, which is expected for the survey methods. The proportion of points above MHW was greater in the Barnegat Bay marshes than in the Delaware Bay marshes. Tidal datum were derived from modeled values (Vdatum), but site-specific tidal monitoring might be considered to validate the datums at reference

Table 1. Linear model outputs for elevation change, where m = slope (in $mm \cdot day^{-1}$); b = intercept; p = probability that slope is significantly different than zero (green text $p<0.05$); SE = standard error; and Rate = slope (in $mm \cdot yr^{-1}$).

Estuary	Station	SET#	Elevation Change				
			m	b	p	SE	Rate
Barnegat	Reedy	1	0.020	13.31	0.003	0.005	7.40
		2	0.025	-3.29	0.002	0.005	9.02
		3	0.001	22.52	0.918	0.012	0.480
	Island Beach	1	0.000	-4.88	0.799	0.002	-0.174
		2	-0.007	-13.03	0.061	0.003	-2.52
		3	-0.002	-12.7	0.469	0.003	-0.883
	West Creek	1	0.143	-20.9	0.007	0.038	52.2
		2	0.001	30.1	0.893	0.011	0.542
		3	0.018	9.06	0.019	0.006	6.43
Delaware	Dividing	1	0.010	1.45	0.065	0.004	3.65
		2	0.013	-3.81	0.009	0.003	4.66
		3	0.021	0.671	0.000	0.002	7.66
	Maurice	1	0.022	-3.07	0.001	0.004	8.08
		2	0.001	-4.18	0.838	0.005	0.385
		3	0.009	-5.38	0.138	0.006	3.32
	Dennis	1	0.012	-2.43	0.000	0.002	4.51
		2	-0.006	-8.22	0.113	0.004	-2.29
		3	0.006	3.88	0.151	0.004	2.03

or project sites. Low marsh optimal growth (i.e. optimal growth for above ground biomass, dark green bars in Figure 8) is well above mean sea level (black horizontal line in Figure 8) at the stations. Island Beach and Reedy have very small tidal prisms so the distance from low marsh optimal growth to mean sea level is small (see Appendix C for raw values). Barnegat Bay marshes, judging from the density of points above MHW, have more high marsh area than those in the Delaware Estuary. Coupled with narrower tidal prisms and the importance of subsurface processes (i.e. Table 4), Barnegat Bay marshes are likely more sensitive to platform elevation manipulations. The frequency and depths of TLP projects in Barnegat Bay will likely be different than in the Delaware Estuary.

To promote marsh ecological health, TLP project designs should set elevation targets within optimal plant growth ranges and ensure that these targets do not require placements that exceed smothering depths. Optimal elevations for high marsh growth are not yet available, so it is especially important to avoid placing too much sediment by adhering strictly to placements less than $D_{smother}$ as productivity could be negatively impacted easily. It is also conducive to consider that typical natural marshes are a mosaic of low and high marshes, cut through by tidal creeks. TLP should therefore seek to mimic the topographical variation observed in natural, healthy marshes. Creeks should be preserved and project goals should not aim to convert all marsh area into one homogeneous habitat. By balancing the degree of manipulation to elevation dynamics or biological function with the expected habitat type (low or high marsh), the most cost-effective and ecologically sound TLP designs can be created.

Table 2. Linear model outputs for accretion (i.e. marker horizons) , where m = slope (in mm·day^{-1}); b = intercept; p = probability that slope is significantly different than zero (green text $p<0.05$); SE = standard error; and Rate = slope (in mm·yr^{-1}).

Estuary	Station	SET#	Accretion				
			m	b	p	SE	Rate
Barnegat	Reedy	1	0.014	-0.061	0.000	0.002	5.10
		2	0.020	-0.205	0.000	0.003	7.29
		3	0.007	6.23	0.103	0.004	2.71
	Island Beach	1	-0.002	3.96	0.413	0.003	-0.834
		2	0.002	1.38	0.676	0.000	0.575
		3	0.009	2.32	0.077	0.005	3.38
	West Creek	1	0.163	-38.3	0.024	0.054	59.5
		2	0.012	0.020	0.000	0.002	4.45
		3	0.010	20.3	0.392	0.011	3.73
Delaware	Dividing	1	0.031	8.60	0.021	0.009	11.3
		2	0.037	5.61	0.001	0.006	13.5
		3	0.019	3.36	0.002	0.004	6.82
	Maurice	1	0.024	7.07	0.004	0.006	8.62
		2	0.011	2.34	0.000	0.002	3.98
		3	0.010	3.06	0.047	0.004	3.62
	Dennis	1	0.016	0.79	0.000	0.002	5.72
		2	0.011	1.06	0.001	0.002	3.94
		3	0.012	0.287	0.005	0.003	4.38

Table 3. Shallow subsidence (SS) for SET-MHs (SS = Accretion - Surface Elevation) and the cumulative depth of material accreted since installation and up until the last SET-MH reading. Negative rates of SS represent subsurface vertical expansion.

Estuary	Station	Days Since Installation	SET#	Shallow Subsidence Rate (mm·yr⁻¹)	Cumulative Accretion Since Install (mm)
Barnegat	Reedy	1500	1	-2.30	21
			2	-1.73	37
			3	2.23	12.9
	Island Beach	1459	1	-0.660	0.33
			2	3.10	8
			3	4.26	19.6
	West Creek	1433	1	7.29	172
			2	3.91	16.9
			3	-2.70	27.8
Delaware	Dividing	1055	1	7.65	29.5
			2	8.88	39
			3	-0.845	20.5
	Maurice	1472	1	0.541	38.8
			2	3.60	18.1
			3	0.295	20.8
	Dennis	1446	1	1.21	22
			2	6.23	12.8
			3	2.35	15.4

Table 4. Projected future changes in marsh elevation at the 6 SSIM stations, assuming a linear extrapolation of recent trends.* Projections include: years to reach 18 cm of accretion; 10 year estimates (from installation to 5 years from last reading) of accretion and platform elevation deficits with respect to SLR rates from NOAA tidal datum. Positive deficits represent elevation surpluses. Values were derived from linear models; see statistical probabilities in Table 1 and 2. 10 year accretion ± 95% confidence interval. The smothering depth ($D_{smother}$), was derived from ratios of local tidal datums.

Estuary	Station	SET#	Years to Accretion = 18 cm (7 in)	10 Year Accretion (mm)	10 Year SLR Deficit of Platform		$D_{smother}$
					mm	in	cm
Barnegat	Reedy	1	35.3	82.2 ± 30	59.1	2.33	2.42
		2	24.7	80.7 ± 33	57.6	2.27	
		3	64.2	27 ± 77	3.89	0.153	
	Island Beach	1	-211	-6.5 ± 11	-29.6	-1.17	2.47
		2	311	-36.5 ± 20	-59.6	-2.35	
		3	52.6	-21 ± 19	-44.1	-1.74	
	West Creek	1	3.67	465 ± 250	442	17.4	13.5
		2	40.4	35.1 ± 69	12.1	0.476	
		3	42.8	69 ± 38	45.9	1.81	
Delaware	Dividing	1	15.2	35.5 ± 32	15.1	0.594	39.7
		2	12.9	40 ± 24	19.2	0.756	
		3	25.9	72.1 ± 15	51.7	2.04	
	Maurice	1	20.1	72.2 ± 25	51.8	2.04	39.4
		2	44.6	-0.591 ± 31	-21	-0.827	
		3	48.9	26 ± 35	5.15	0.203	
	Dennis	1	31.3	40 ± 11	19.2	0.756	39.3
		2	45.5	-30 ± 22	-50	-1.97	
		3	41.0	22.8 ± 22	2.37	$9.33 \cdot 10^{-2}$	

*Marsh platform elevation responses to sea level are likely nonlinear, especially over long periods of time

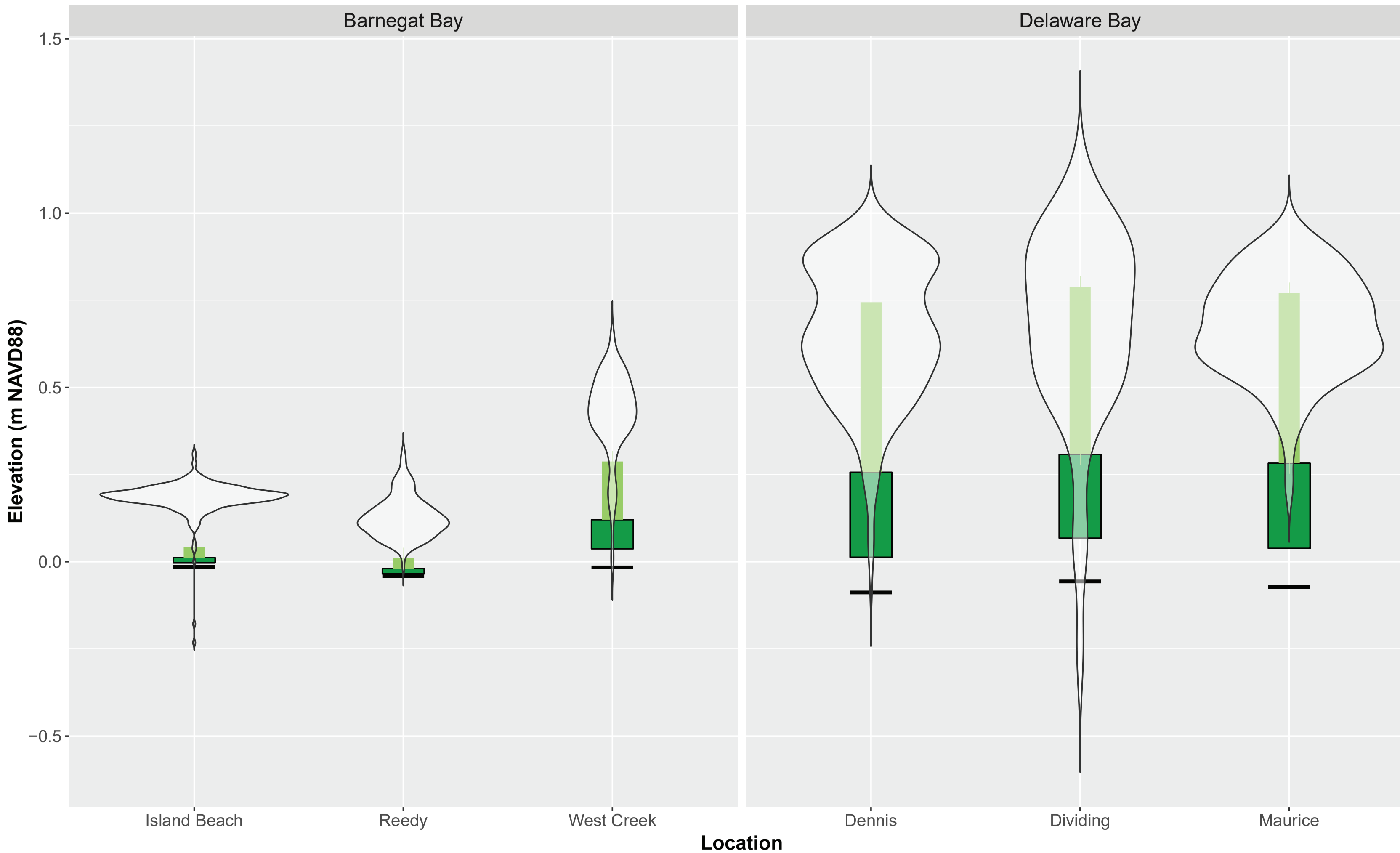

Figure 8. Violin plots of RTK GPS elevation survey data for Barnegat Bay and Delaware Estuary stations, including site-specific calculations of low marsh optimal growth (dark green bars). Light green bars show the upper extent of the tidal prism (from the top of optimal low marsh growth to MHW). Mean sea level is depicted with black horizontal lines. Datum were calculated using NOAA's Vdatum tool. Dataset sizes for each station were 265, 140, 237, 324, 159, and 153 points for Island Beach, Reedy, West Creek, Dennis, Dividing, and Maurice, respectively. See Appendix C for raw values of tidal datums and optimal growth ranges. It is important to note that these values only reflect current conditions (i.e. elevation capital) and are not necessarily indicative of vulnerability to sea level rise caused by long term elevation dynamics.

Application of Data

How to Use These Data

Monitoring data such as those presented here from MACWA SSIM stations in New Jersey can be used in many ways, such as to:

- Detect marsh vulnerability;
- Understand underlying stressors that govern vulnerability;
- Consider and help design potential appropriate intervention tactics, and;
- Monitor and assess performance of interventions.

For example, these data can provide quantitative measurements of natural elevation dynamics, such as accretion and shallow subsidence. Reference data from SSIM stations provide information on the magnitude of these processes. Comparisons among stations yield an understanding of how elevation metrics vary from marsh to marsh, and to what degree. They guide ecologically sound interventions. With TLP, these data might be used to set goals for sustaining robust low marsh and understanding what placement depths might be too much and what elevations might yield the best biological responses to help support natural biogeomorphic feedbacks. Having these data upfront is also useful for estimating the necessary financial investment required for dredging operations based on what the marsh potentially needs.

Case Study 1: Dennis Creek

As a hypothetical, if there was interest in using TLP within a tract to enhance elevation capitol of a marsh along Dennis Creek, planners can review data from the Dennis SSIM station. From Tables 1 and 2, one can see that elevation change varied from -2 to more than 4 $mm \cdot yr^{-1}$ and accretion was approximately 4.7 $mm \cdot yr^{-1}$. Shallow subsidence ranged from 1 to 6 $mm \cdot yr^{-1}$, which suggests that elevation changes are mediated partially by subsurface processes, such as below ground plant productivity. The local rate of sea level rise at Dennis is ~4.5 $mm \cdot yr^{-1}$. Only data from SET 1 had a platform rate of change that was equal to or greater than this LSLR (i.e. keeping pace). SETs 2 and 3 had deficits of ~6 and 2 $mm \cdot yr^{-1}$, respectively. From the beginning of the study to the next five years, SET 2 would have an elevation deficit of ~50 mm (5 cm, 2 in)(Table 5), but SET 3 might still have some elevation capital (i.e. less urgency to intervene). If the goal is to enhance resilience to SLR by a factor of 25 years,* at most ~14 cm of material might be considered. A geomorphologically-based optimal placement depth may therefore range from 5-14 cm (2-5.5 in).

At Dennis, the lowest elevation for optimal low marsh plant growth is 0.3 m NAVD88. Tracts of marsh that consistently fall below this threshold might be areas of interest for placement. But, placing only 2-5.5 inches of material (as surmised above) in these areas might not be enough to obtain desired results. This would be planning for low marsh creation, which might require additional steps, such as planting *S. alterniflora*, rather than manipulating elevation dynamics in the high marsh. Since marsh loss most frequently occurs along shorelines, placing material along edges in order to create low marsh areas is an option with a lot of merit, but tactics for this are seldom discussed and not well developed. Future studies will shed more light onto how to perform this tactic successfully.

*To calculate this, divide 25 by the number of years to accrete 18 cm and multiply by 18 cm

All planned final placement elevations at Dennis should likely not exceed 1.2 m NAVD88, nor should final placement depths be greater than ~40 cm (16 in) to avoid smothering impacts (e.g. Figure 8, Table 4). This is especially true for high marsh areas. In high marshes, target depths should follow the 2-5.5 inch placement threshold, focusing heavily on cultivating appropriate biological responses and less on attaining consistent elevation targets, provided that the final elevations are below the upper elevation reference threshold (i.e. ~1.2 m NAVD 88 at Dennis).

It would be impractical to have elevations within the project area fall below 0.0 m NAVD88 at any point in time, as that is the lowest extent of optimal growth at Dennis. Monitoring for this is key to long term success and would be a part of an adaptive management plan. Plans might also need to be augmented to include vegetation plantings if target elevations require placement depths >40 cm. This is generally not recommended since plantings are costly and survivorship is generally low; other tactics might need to be considered, such as using the dredged material to back-fill living shorelines.

Unvegetated areas which appear to be holding excess water at low tide, but have elevations within optimal low marsh growth ranges, may be candidates for hydrological interventions to improve tidal connectivity, without the need for TLP. Additional surveying and data collection (e.g. hydrological monitoring) should be carried out for those areas.

The reference data provided here are a guide to estimate target elevations and depths of placed sediment before finalized targets are calculated, but it is important that these are not the only tool used for planning these projects. Field sampling of local elevations, vegetation robustness, and/or hydrology is imperative to make the soundest ecologically-based targets which fit site-specific needs.

Case Study 2: West Creek SET 1

The West Creek SSIM station was installed in 2010; in 2012, the local mosquito control authority began managing the marsh to control mosquito populations. The method used is called Open Marsh Water Management (OMWM). The goal of OMWM is to create open water ponds, which are unsuitable for mosquito breeding. Backhoes are used to dig these ponds and the tailings are casted onto the adjacent marsh surface (Figure 9). These mosquito management tactics were carried out at the West Creek SSIM station, allowing for an opportunity to study the effects of sediment placement on a marsh surface in southern Barnegat Bay.

Figure 9. Open marsh water management (OMWM) taking place around SET 1 at West Creek in 2012. Photo taken by PDE staff.

In 2012, these activities took place near SET 2, and permanent vegetation plots were affected, although no impact was found at the SET itself. Four years later, vegetation impacts were still evident (Figure 10).

In the summer of 2013, activities took place at SET 1, directly impacting the SET. OMWM activities had placed about 200 mm (20 cm or 7.9 in) of sediment onto the SET-MH, as calculated from MHs several months after OMWM had been completed. To standardize trends, 200 mm of sedimentation was subtracted from the first post-OMWM reading (Figure 11). Before sediment placement, SET 1 appeared to be accumulating elevation at ~5 $mm \cdot yr^{-1}$ (linear regression, $p<0.01$), similar to SET 3. After OMWM, this changed to -25.7 $mm \cdot yr^{-1}$. Despite a net increase in platform elevation due to added materials, the rate of elevation change after placement precipitously decreased by more than 25 $mm \cdot yr^{-1}$ (linear regression, $p<0.05$). Whether this change was due to continued post-placement consolidation, subsurface compaction, or by reductions in plant productivity was not investigated, but all three factors likely played a role. These data suggest that at West Creek SET 1, platform elevation dynamics continued to adjust over a period of several years after sediment was placed. In conclusion, despite a total increase in elevation capital, elevation dynamics were impacted greatly for some time following platform manipulations. Sediment placement actually appeared to hasten loss of elevation capital compared to undisturbed SETs at West Creek.

Using the other SET-MHs at West Creek (i.e. SETs 2 and 3), estimated threshold values can be compared to actual placement depths. From Table 4, we can estimate that if the goal was to add 25 years of accretion to these marshes, the upper threshold would be approximately 11 cm, 9 cm less than what was placed on the marsh in 2012. This upper threshold is similar to $D_{smother}$, which is 13.5 cm. SET 3 through this time period kept pace with sea level. The rate of elevation change at SET 2 was less than sea level rise, but in the immediate future, this site might still have adequate elevation capital. If we wanted to ensure that elevation capital at SET 2 was similar to SET 3 in the next 5 years, we might consider a placement depth of approximately 3 cm (the difference between their 10 year deficits). Since $D_{smother}$ is greater than the 25 year accretion estimate, the maximum placement depth is 11 cm. Optimal placement depths, however, would likely be much less as these marshes already sit quite high in the local tidal prism (e.g. Figure 8). If placement was deemed absolutely necessary, recommended placement depths would ranged between 3-11 cm (1-4 inches). It is likely that negative effects were experienced at SET 1 because too much sediment was placed on the surface.

Although this case study is one example from a non-TLP manipulation scenario, and more monitoring and studies will need to be carried out, it provided an opportunity to examine marsh responses to sediment placement. The lessons learned from West Creek SET 1 clearly demonstrate how unexpected outcomes might result from sediment placement projects. TLP planning should consider that:

- Elevation adjustments may take years to equilibrate;
- Rates of elevation change can be adversely affected by sediment placement;
- A platform currently gaining elevation can have a precipitously negative response, despite the initial increase in absolute elevation; and
- The plant community may take years to recover (e.g. West Creek SET 2, Figure 10), which could have negative effects on elevation dynamics, especially in systems that depend heavily on plant production for elevation building.

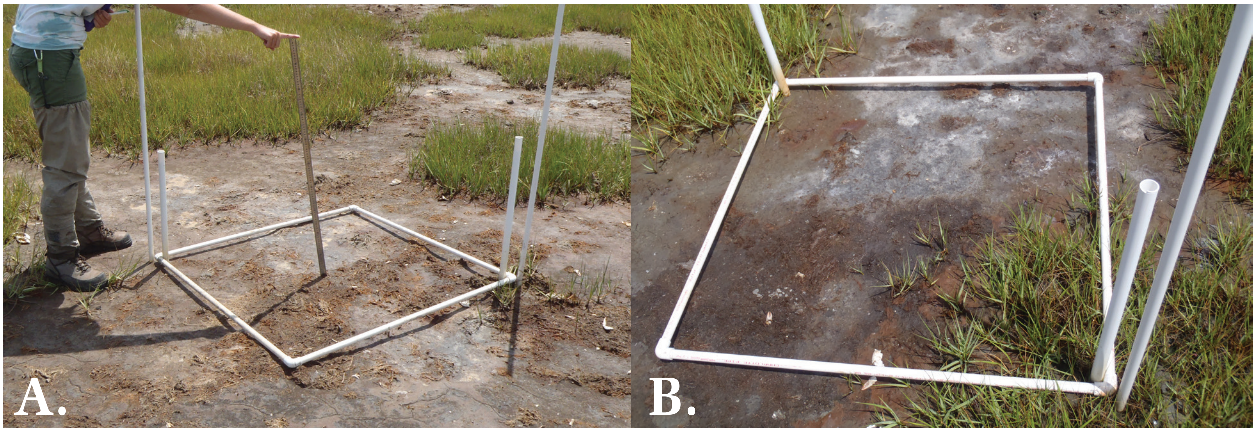

Figure 10. In 2014, a permanent vegetation plot at SET 2 in West Creek was still impacted by cast materials from OMWM activities done in 2012 (A) and two years later, in 2016 (B), vegetation recovery was only reported at <10% within the same plot. Photos by PDE (A) and BBP staff (B).

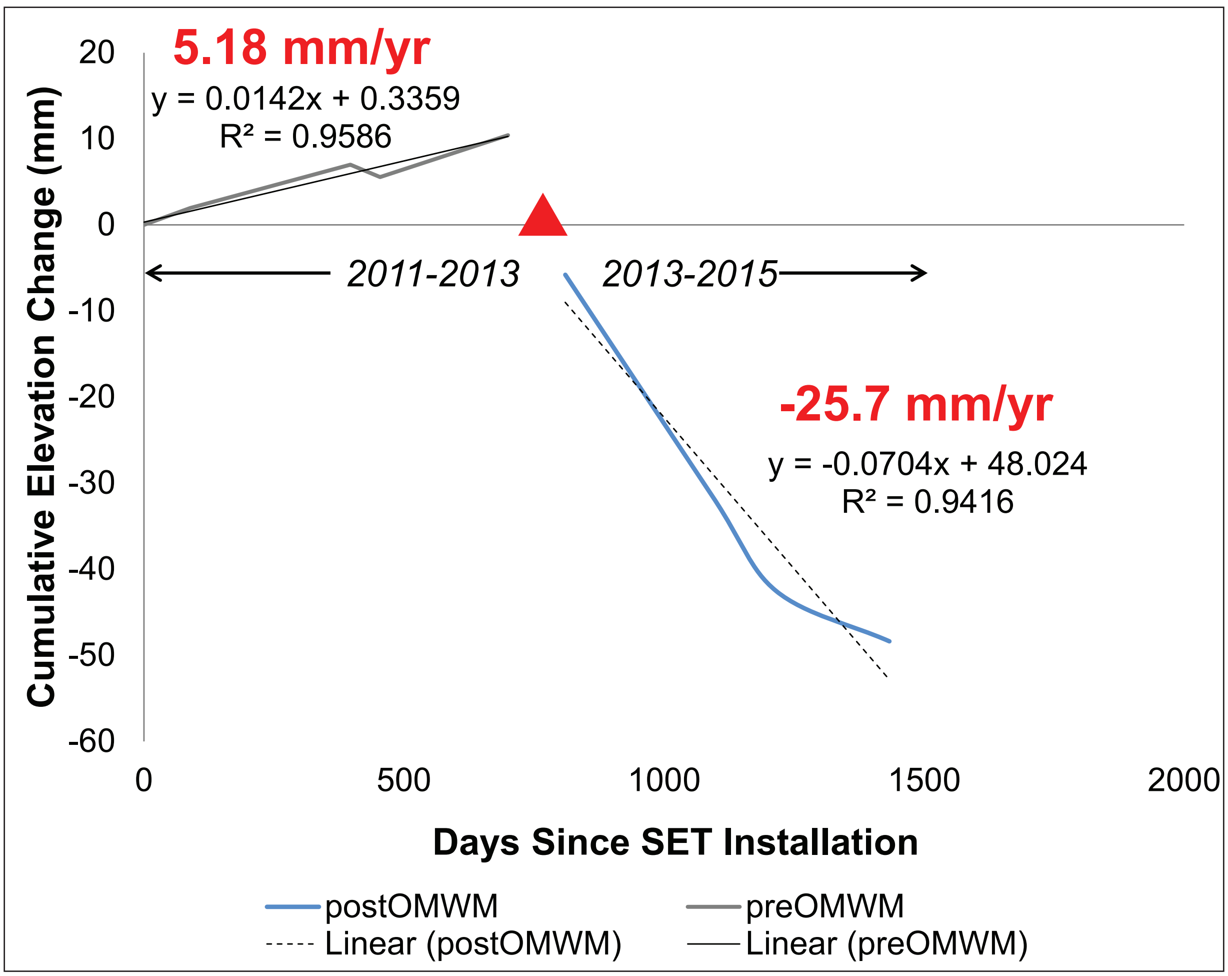

Figure 11. Alteration of elevation change rates after OMWM at West Creek SET 1 in Barnegat Bay. OMWM activities took place during the summer of 2013 (red triangle). About 200 mm (~7.9 in) of material was cast onto the marsh surface, as discerned from marker horizons.

The success of future TLP projects in the Mid Atlantic relies on the identification of characteristics of marsh condition which dictate how the marsh will respond to sediment placement. Marshes of varying conditions likely have different responses to the types and depths of sediment placement, so matching designs to local ecology is important. Hazards should be carefully considered when designing TLP targets to ensure that only the desired ecological responses are achieved.

Summary

Coastal wetland elevation dynamics and expected responses to sea level rise should be understood before these processes are manipulated at any location through TLP (i.e. surface accretion). Quantitative examples of these processes were discussed for the Delaware and Barnegat Bay Estuaries using long term datasets from established wetland monitoring programs (i.e. SSIM). Reference data from MACWA estimate elevation deficiencies and gauge appropriate ranges for target elevations and depths. The surface elevation and accretion data provided in this report illustrate how long term monitoring efforts can enhance the designing and planning of coastal wetland intervention tactics. Long term monitoring provides vital reference data to clarify design criteria of projects, such as TLP, and essential frames of reference for monitoring project performance.

Sediment application, such as by TLP, is one of many new promising coastal wetland enhancement techniques. Depending on sediment type and marsh condition, TLP might represent a sound tactic for a subset of vulnerable marshes. However, other tactics aimed at restoring hydrology or stemming high rates of edge erosion might be preferred alternatives at more locations than for TLP. Some New Jersey marshes are not immediately vulnerable, and until these tactics become better understood, those marshes probably should be "no action" alternatives.

In the future, we hope to utilize these data to create decision-trees to guide site specific intervention strategies and provide additional guidance on design and project monitoring. We also hope to use scientific approaches and MACWA frameworks to fill data or knowledge gaps which still exist in New Jersey, such as expectations on post-consolidation processes and rates of compaction by various sediment types and depths.

Notes

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Appendix A: Additional Information on Site Specific Intensive Monitoring Stations

Table 5. SET array descriptions for SSIM stations in the Barnegat Bay and Delaware Estuaries. For up/down stream arrays, spatial arrangements are described as each SET's linear distance from the main tidal body's confluence (mouth) with its respective bay. For transects, the linear distance is given from the center of the array.

<table>
<tr><th rowspan="2">Estuary</th><th rowspan="2">Station</th><th rowspan="2">Main Tidal Body</th><th rowspan="2">Array Style</th><th rowspan="2">Year Installed</th><th colspan="2">SET Array</th></tr>
<tr><th>SET #</th><th>Distance to Mouth (km)</th></tr>
<tr><td rowspan="7">Barnegat</td><td rowspan="3">Reedy</td><td rowspan="3">Reedy Creek</td><td rowspan="3">Up/ Down-stream</td><td rowspan="3">2010</td><td>1</td><td>0.25</td></tr>
<tr><td>2</td><td>0.65</td></tr>
<tr><td>3</td><td>0.85</td></tr>
<tr><td>Island Beach</td><td>Barnegat Bay</td><td>Transect</td><td>2011</td><td>NA</td><td><1</td></tr>
<tr><td rowspan="3">West Creek</td><td rowspan="3">Dinner Point Creek</td><td rowspan="3">Up/ Down-stream</td><td rowspan="3">2010</td><td>1</td><td>0.54*</td></tr>
<tr><td>2</td><td>0.54*</td></tr>
<tr><td>3</td><td>1.5</td></tr>
<tr><td rowspan="7">Delaware</td><td rowspan="3">Dividing</td><td rowspan="3">Dividing Creek</td><td rowspan="3">Up/ Down-stream</td><td rowspan="3">2012</td><td>1</td><td>1.3</td></tr>
<tr><td>2</td><td>2.2</td></tr>
<tr><td>3</td><td>2.8</td></tr>
<tr><td>Maurice</td><td>Maurice River</td><td>Transect</td><td>2010</td><td>NA</td><td>3.7</td></tr>
<tr><td rowspan="3">Dennis</td><td rowspan="3">Dennis Creek</td><td rowspan="3">Up/ Down-stream</td><td rowspan="3">2011</td><td>1</td><td>1.3</td></tr>
<tr><td>2</td><td>2.0</td></tr>
<tr><td>3</td><td>4.2</td></tr>
</table>

*Same river kilometer, but located on opposite sides

Appendix B: Coastal Geography and Tidal Range Variation in New Jersey

The coastal environments of New Jersey consist of the riverine Delaware Estuary, along the state's western border from Cape May Point to Trenton, NJ; the Raritan Bay or NY-NJ Harbor, which is the confluence of three major riverine systems: the Raritan, the Hackensack, and Hudson Rivers; and a series of shallow lagoon complexes that line the east coast from Sandy Hook to the Cape May Harbor, with major embayments including Barnegat Bay, Great Bay, Great Egg Harbor Bay, and Stone Harbor. Tidal amplitudes vary among these systems due to variations in geomorphology of each (Table 6), but salt marsh plant assemblages are similar, consisting mostly of *Spartina alterniflora, Spartina patens, Distichlis spicata, Phragmites australis,* and *Iva frutescens*. The data presented here were from salt marshes of the Delaware and Barnegat Bays; there are also SSIM stations in the freshwater tidal reaches of the Delaware River. New stations are planned for Stone Harbor and the Raritan Bay.

Table 6. Tidal ranges (MHW-MLW) observed throughout the coastal regions of New Jersey, as obtained from NOAA tidal stations < https://tidesandcurrents.noaa.gov>.

State	Location	Water Body	Salinity	NOAA Tidal Station ID	Mean Tidal Range	
					Feet	Meters
NJ	Trenton Marine Terminal	Delaware River	Fresh	8539993	8.18	2.49
NJ	Burlington	Delaware River	Fresh	8539094	7.30	2.23
NJ	Tacony-Palmyra Bridge	Delaware River	Fresh	8538886	6.59	2.01
PA	Bridesburg	Delaware River	Fresh	8546252	6.38	1.94
PA	Philadelphia	Delaware River	Fresh	8545240	6.10	1.86
NJ	Paulsboro, Mantua Creek	Delaware River	Fresh	8538512	5.64	1.72
PA	Marcus Hook	Delaware River	Fresh	8540433	5.59	1.70
DE	Delaware City	Delaware River	Brackish	8551762	5.44	1.66
DE	Reedy Point	Delaware River	Brackish	8551910	5.34	1.63
NJ	Ship John Shoal	Delaware Bay	Saline	8537121	5.61	1.71
NJ	Fortescue Creek	Delaware Bay	Saline	8536931	5.85	1.78
NJ	Bidwell Creek Entrance	Delaware Bay	Saline	8536581	5.67	1.73
NJ	Cape May	Delaware Bay	Saline	8536110	4.85	1.48
NJ	Wildwood Crest	Eastern Coast	Saline	8535835	4.31	1.31
NJ	Townsend Inlet	Eastern Coast	Saline	8535375	3.96	1.21
NJ	Longport, Risely Channel	Eastern Coast	Saline	8534836	3.78	1.15
NJ	Atlantic City	Eastern Coast	Saline	8534720	4.02	1.23
NJ	Great Bay, Shooting Thorofare	Eastern Coast	Saline	8534319	2.88	0.88
NJ	Barnegat Bay Inlet	Eastern Coast	Saline	8533615	2.15	0.66
NJ	Sandy Hook	Raritan Bay	Saline	8531680	4.70	1.43
NJ	Keyport	Raritan Bay	Saline	8531545	5.05	1.54
NJ	Rahway River	Rahway River	Brackish	8531077	5.38	1.64
NJ	Point No Point	Passaic River	Brackish	8530743	5.22	1.59
NJ	Hackensack River	Hackensack River	Fresh	8530278	6.00	1.83

Appendix C: Tidal Datum and Optimal Growth Range Data

Table 7. Raw tidal datum and OPGE ranges for SSIM stations used to create Figure 8.

Estuary	Station	MSL	Tidal Range	MHW	MLW	Optimal Range		
						m	m NAVD88	
		m NAVD88	m	m NAVD88		Range	Upper	Lower
North Inlet, SC*		-0.109	1.43	0.552	-0.878	0.2	0.152	-0.048
Barnegat	Reedy	-0.0411	0.107	0.0102	-0.0970	0.0150	-0.0198	-0.0348
	Island Beach	-0.0149	0.109	0.0424	-0.0670	0.0153	0.0118	-0.00350
	West Creek	-0.0163	0.597	0.288	-0.309	0.0834	0.121	0.0372
Delaware	Dividing	-0.0565	1.72	0.789	-0.930	0.240	0.308	0.0674
	Maurice	-0.0722	1.75	0.771	-0.975	0.244	0.282	0.0383
	Dennis	-0.0881	1.74	0.744	-0.999	0.244	0.257	0.0128

*from Morris et al. 2002