ABSTRACT

Title of Thesis: MARSH ELEVATION AND ACCRETION DYNAMICS ALONG ESTUARINE SALINITY GRADIENTS: OBSERVATIONAL AND EXPERIMENTAL STUDIES

Leah Hope-Menzies Beckett, Master of Science, 2009

Thesis directed by: Associate Professor Andrew H. Baldwin

Department of Environmental Science and Technology

Chesapeake Bay marshes are threatened by sea level rise and have experienced degradation as a result of saltwater intrusion and increased water levels. Rates of elevation and accretion change and vegetation communities may be affected by salt water intrusion and other processes as a result of sea level rise. An observational study of the Nanticoke River, a tributary to the Chesapeake Bay, utilizing surface elevation tables (SET) reflected that during the course of a two year study period, rates of marsh elevation change differed significantly along an estuarine salinity gradient. Surface elevation of oligohaline marshes decreased during the monitoring period and were significantly different from mesohaline marshes which increased in elevation. An experimental study in Patuxent River tidal freshwater marshes in which plots were irrigated with

saltwater indicated that with saltwater intrusion vegetation communities may become less diverse.

MARSH ELEVATION AND ACCRETION DYNAMICS ALONG ESTUARINE SALINITY GRADIENTS:
OBSERVATIONAL AND EXPERIMENTAL STUDIES

by

Leah Hope-Menzies Beckett

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Advisory Committee:
Associate Professor Andrew Baldwin, Chair
Professor Michael Kearney
Professor Martin Rabenhorst

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I. INTRODUCTION

IMPORTANCE OF WETLANDS

Coastal wetlands are an exceedingly valuable and unique resource. The ecological services they provide are vital to the economy and health of the people who rely on them, and to the species they harbor. Wetlands provide ecosystem services that have an estimated worth of 5 trillion dollars per year, and are the most ecologically and economically valuable of all coastal wetlands (Costanza et al. 1997, Kirwan et al. 2008). Coastal wetlands act as buffers from hurricanes and floods, filters of pollutants from runoff, nurseries for commercial fish species, and habitats for hundreds of endangered species. Avian and fish species are highly reliant on wetlands. Over 80% of migratory bird species and 95% of the commercial fish and shellfish species are dependent on wetlands (Mitsch and Gosselink 1993). In addition, wetlands mitigate floods (Jiang et al. 2007), sequester and transform run off pollutants, and recharge upland water tables in the dry summer months.

WETLAND LOSS

Coastal wetlands are increasingly threatened by anthropogenic causes, including dredging river channels, high doses of fertilizers and nutrients from run off (Swarzenski et al. 2008), diverting freshwater inputs (Barras et al. 2003), and increased sediment erosion. However, perhaps the greatest threat is rising sea levels because of warming global temperatures (Kearney et al. 1994). In the last 10,000 years since the last glaciation, the rate of sea level rise has not always been constant (Kirwan and Murray 2008, Douglas 2001). Historically, sea levels have risen slowly, allowing wetlands to form and persist; however, global warming has greatly escalated the rate of eustatic (background) sea level rise. Eustatic sea level rise [1-2 mm/yr (Gornitz 1995)] acts additively with land subsidence to create rates of relative sea level rise that may be higher than coastal wetlands can adjust to. Varying rates of sea level rise over time is one of the greatest factors in marsh loss or persistence (Ward et al.1998, Patrick and DeLaune 1990). Marsh surfaces must be able to build enough mineral and organic matter to keep abreast of mean water level; however, rates of sea level rise have accelerated enough that many marshes cannot accrete sufficiently (Ward et al.1998).

Gulf Coast marshes have already experienced widespread submergence and loss. Louisiana alone is exhibiting one of the greatest rates of loss thus far at 12,540 ha/yr (Turner 1990). Factors influencing this loss include water table draw down and subsequent surface drying (Patrick and DeLaune 1990), freshwater input diversion and subsequent increased salinity and fewer sediments, and greatest of all, sea level rise and land subsidence. Some marshes along the Eastern United States Atlantic coast have maintained elevation despite increasing sea levels (Neubauer 2008), while many other Chesapeake Bay marshes have already begun to exhibit loss. Ward et al. (1998) found that marshes along the Nanticoke River and at Monie Bay are not keeping pace with sea level rise as evidenced by long term accretion rates, although high short term accretion rates may partially mitigate the effects of increased sea level.

Submergence, even at a small scale, increases hydroperiod depth and duration dramatically, in turn, this further escalates submergence (Reed and Cahoon 1992). Accretion rates are highest along the river/tidal creek bank where a natural levee forms, leaving interior marshes more vulnerable to loss because of decreased accretion rates (Neubauer 2008, Salinas et al. 1986). Sea level rise brings higher water levels, greater tidal flooding durations, and sea water intrusion into formerly freshwater areas (Tiner 1993).

TIDAL FRESHWATER MARSH VULNERABILITY

Many studies have examined elevation and accretion dynamics in salt marshes (e.g. Warren et al. 1993, Fitzgerald et al. 2008); in contrast, tidal fresh water marshes may be at a greater risk of loss and are poorly understood. To date, few studies have examined the elevation and accretion dynamics, as well as tidal freshwater marshes' ability to respond to sea water intrusion. In fact, tidal freshwater marshes may be at a greater risk not only because of greater inundation and salt stress, which inhibits the annual-dominated vegetation's ability to reestablish (Portnoy and Giblin 1997), but also because of a potential switch from methanogenesis, the dominant decomposition pathway in tidal freshwater marshes, to sulfate reduction, the more energy efficient decomposition process that occurs when sulfate, abundant in sea water, is present (Capone and Kiene 1988). In comparison to the more recently formed submerged upland marshes at the mouth of the Nanticoke estuary, tidal freshwater and oligohaline marshes in the Nanticoke estuary were formed in flooded river valleys after the last glaciation and are meander marshes with thicker organic layers (see rod depths in Table 2.1) putting them at a greater risk of damage due to higher decomposition rates than submerged upland marshes further downstream (which are mesohaline in the Nanticoke estuary). Additionally, the soils of tidal freshwater marshes are more erodible than those of salt marshes (Odum 1988).

Tidal freshwater marshes can be defined as marshes upstream of the oligohaline zone in flooded river valleys (Odum 1988). They have average salinities of <0.5ppt and are associated with rivers (Mitsch and Gosselink 2000). Tidal freshwater marshes make up about 1/3 of coastal wetlands in the United States (Tiner and Burke 1995), and they are the most biodiverse of the coastal wetland types. Tidal freshwater wetlands support hundreds of endangered species of both plant and animal, a varied plant community, and bird and fish populations that are greater than those in the saline estuaries (Odum 1984). Tidal freshwater marshes are formed in flooded river valleys, limiting their geographical range, and therefore are difficult to re-establish once submerged.

MARSH ELEVATION AND ACCRETION

Accretion

The ability of marshes to accrete vertically at a rate sufficient to keep pace with rising sea levels is crucial to their survival (Stevenson et al. 1985). The rate of accretion in each marsh must equal or exceed the rate of sea level rise [1-2mm/year (Gornitz 1995)] in order to not be submerged. Accretion is the balance of organic and mineral particulate inputs and surface erosion that creates marsh substrates. Sediment supply is a major factor in determining whether marshes can accrete sufficiently. A marsh that has an ample sediment supply can keep pace with rising water level; however, marshes that do not have enough sediment input break up and are converted to open water (Patrick and DeLaune 1990). Accretion rates are highly variable over time and spatially (Kearney et al. 1994; van Wijnen and Bakker 2001). Varying vegetation density can affect sediment trapping and also the amount of litter organic matter (Neumeier and Amos 2006). Additionally, spatial variation of accretion rates is affected by the microtopography common in oligohaline and mesohaline marshes, and the proximity to sediment sources, i.e. tidal channels (Kearney et al. 1994). Marshes that are inundated more frequently and for longer periods receive larger sediment loads (Reed 1990); however, despite longer inundation durations in interior marshes, interior marshes have lower accretion rates compared to creek bank marsh areas because sediment is deposited on natural levees formed there (Neubauer et al. 2002). Because of this, interior marshes are at a greater risk of loss and exhibit ponding and degradation before creek edge marshes.

Accretion rates are highest in tidal freshwater marshes and decrease proceeding downstream to brackish marshes (Craft 2007).

Elevation

Marshes can lose elevation, or subside, because of a variety of factors. Deep processes such as tectonic subsidence and subsurface water extraction (Patrick and DeLaune 1990), as well as site specific factors including differing rates of primary productivity, differences in sediment supply, climate, decomposition, tidal range, and autocompaction influence marsh elevation (Cahoon et al. 2006). Local factors that may affect marshes more than eustatic sea level rise include coastal geomorphology, sediment supply and frequency of major storms that may alter whether estuary systems are ebb or flood dominated, which in turn alter sediment deposition and erosion dynamics (Cahoon et al. 1999). Because of local factors such as deposition, erosion, and hydroperiod working together, site specific information is required to determine the status of each wetland.

Temporal variation of elevation is caused by factors such as root growth and death, decomposition, and the shrink-swell of marsh organic soils associated with seasonal and water storage variations.

Elevation measurements include the effects of processes such as tectonic movements (not measured by the SET), compaction, vegetation dynamics, and also included in elevation measurements are accretion rates. Accretion is a surface process that also impacts overall elevation measurements.

OBJECTIVES

It is crucial to understand in what ways elevation and accretion changes affect the marshes' ability to keep up with sea level rise. Because each marsh has a unique combination of characteristics (sedimentation rates, physiographic setting, etc.), the dynamics controlling accretion and subsidence of marshes vary with each marsh. Site specific information is needed to predict how each marsh will react to eustatic sea level rise and coastal submergence (Cahoon 1999). To better understand the current dynamics of Chesapeake Bay marshes, especially tidal freshwater marshes to sea level rise, two studies were undertaken: an observational study on the Nanticoke River and an experimental study on the Patuxent River.

The objectives of these studies are twofold:

I.To gain an understanding of marsh elevation dynamics along the Nanticoke estuarine gradient, comparing tidal fresh, oligohaline,and mesohaline marshes, and

II. To experimentally investigate the effects of salt water intrusion on tidal freshwater marsh soil elevation and accretion dynamics.

HYPOTHESES

- Spatial variation of accretion and elevation change has a recognizable pattern following the Nanticoke River salinity gradient.
- Rates of elevation and accretion increase are highest in tidal freshwater marshes and decrease proceeding seaward across the estuary.
- With increased salinity, vegetation communities will change; specifically that there will be fewer species, higher vegetation death, and colonization by more salt-tolerant species.
- There will be a switch from methanogenesis to sulfate reduction at Patuxent experimental plots following addition of Salinity treatments, causing rapid subsidence and a drop in the elevation of marsh surface.

II. MATERIALS AND METHODS

The responses of tidal marshes to increased salinity resulting from sea level rise have been explored in two parts: 1) examining present elevation dynamics along a 50-km gradient of the Nanticoke River and 2) a field experiment was implemented simulating salt water intrusion at the Patuxent River.

NANTICOKE RIVER OBSERVATIONAL STUDY

Monitoring at the Nanticoke River began in July of 2007 and continued until April 2009. The Nanticoke River portion of the project was observational. Elevation change and accretion rates were monitored from October 2007-April 2009 in order to determine if there were trends along a salinity gradient

Hypotheses

There will be a significant difference in accretion and elevation rates, and identifiable trends along the salinity gradient of the Nanticoke River for those parameters. Tidal freshwater marshes will have a greater amount of accretion elevation increase compared to oligohaline and mesohaline marshes.

Study Site

The observational study was conducted in tidal marshes along a 50km gradient of the Nanticoke River. The Nanticoke River is on Maryland's Eastern Shore (Figure 2.1) and extends from the Chesapeake Bay, one of the largest microtidal estuaries in the world (Ward et al 1998) into Delaware.

Figure 2.1 Nanticoke River on the Delmarva peninsula (www.wikipedia.org/wiki/Nanticoke River)

The Nanticoke River has a 2,934 km^2 watershed that is the most biologically diverse watershed on the Delmarva peninsula (Nature Conservancy 2009). The marshes of the Nanticoke River range from tidal fresh 50 km upstream near Sharptown, MD to mesohaline at the confluence of Chesapeake Bay. These marshes range from relatively young to mature stage marshes with characteristic extensive drainage and creek systems that vary dramatically over decades (Ward et al 1998). Marshes near the mouth of the estuary are submerged upland

and further upstream are estuarine and tidal fresh marshes (Kearney et al. 1988) that formed between river meanders after the last glaciation from the drowned river valley. The Nanticoke estuary, a coastal plain estuary, experiences a semidiurnal tidal regime (two high tides and two low tides a day), is ebb dominated (Kearney et al 1988), with a tidal range that is approximately 0.61 m (USGS 2009). Local sea level rise measured by the National Oceanographic and Atmospheric Administration (NOAA) at Cambridge, MD from 1943-2006 was 3.48 ± 0.39 mm/yr (NOAA 2009). Five sites were selected along a 50 km gradient of the Nanticoke River (Figure 2.2). At each site, there were 3 replicate sites (A-C).

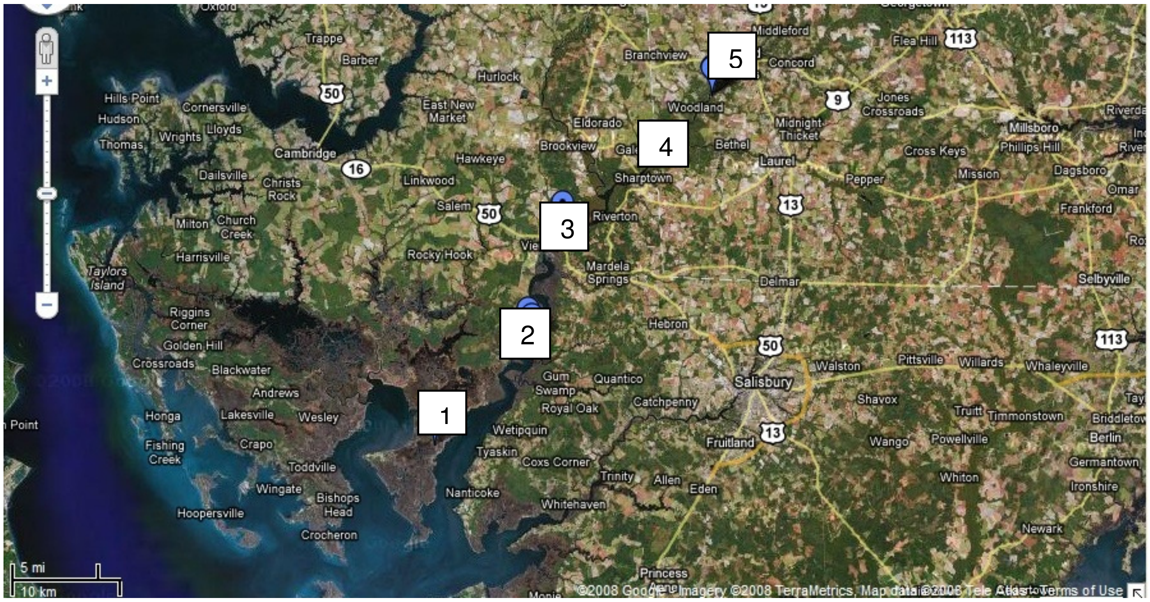

Figure 2.2: 5 Sites on the Nanticoke River: At each site there are 3 SETs about 1-2 km apart from one another, the sites are about 10-16 km apart from one another. Site 5 is the farthest upstream (maps.google.com).

Sites were selected to be in interior marshes, away from the natural levee that forms along the tidal creek or river channels. Interior marsh sites were chosen because they should not receive as many allocthonous sediments as channel edge sites and are thus less likely to keep up with rising sea levels. Sites were randomly chosen using a random numbers table signifying the number of paces from channel edge. Sites ranged from 35m-80m from the channel.

Soils of the Nanticoke River

During selection of sites, 1.3 m soil cores were taken and described (Table 2.1), and soil organic matter content was determined by loss on ignition. The highest percentage of soil organic matter was found at Site 1, a submerged upland marsh, having an average of 50.2%. Site 1 was followed by Site 3, a meander marsh, having 43.0% organic matter (OM). Site 4 had 37.4% OM, Site 2, a meander marsh having the greatest depth of organic soil layers, had 30.7%, and Site 5 had 23.6% soil organic content. The depth of refusal for surface elevation table (SET) benchmark survey rods driven into the soil is presented in Table 2.1 as a measure of relative organic soil depth (see Chapter 3, SET Installation). Basic soil characteristics and primary soil series at each site were obtained off-site through NRCS web soil survey (NRCS 2009) (Table 2.1).

Table 2.1: Soil descriptions of Nanticoke estuary SET sites. Soil descriptions from NRCS web soil survey mapping tool (NRCS 2009). Depth to Refusal is the length of survey rods driven to a point of refusal. The three values are of replicate sites A-C. A is the first number listed followed by B and C. Percentages in column 2 represent percentage of map unit series composed of named series.

SET Site	**Primary Map Unit Series**	**Land Form**	**Field Observational Notes**	**Frequency of Flooding and Depth to Water Table**	**Typical Profile**	**Depth to Refusal**
1	Honga Peat (80%)	Submerged Upland Tidal Marsh	Of 1.3 m core, 0-25 cm very fibrous/organic, 25-100 cm very firm, 100-130cm light grey clay with visible plant parts	Frequently, 0 cm	0-17.8 cm peat	2.7 m 2.7 m 2.4 m
2	Transquaking and Mispillion (80%)	Tidal Marsh	0-40 cm, little coarse organic material, 40-100 cm, more fibric, 100-130 cm, soupy	Very frequently, 0-12.7 cm	0-116.8 cm: mucky peat 116.8-165.1 cm: muck 165.1-203.2 cm: silty clay loam	10.8 m 14.7 m 13.5 m
3	Nanticoke Silt Loam (70%)	Marshes	0-130 cm highly organic and fibric, peat-like	Frequent, 0 cm	0- 25.4 cm: silt loam	9.8 m 11.6 m 7.3 m
4	Nanticoke and Mannington (90%)	Tidal flats, mud flats, floodplains	0-60 cm, plant parts visible 60-100, more clayey, 100-130 cm, highly organic	Very frequently, 0-12.7 cm	0-25.4 cm: silt loam 25.4-61.0 cm: silt loam 61.0-203.2 cm:silty clay loam	8.6 m 9.5 m 10.4 m

5	Nanticoke and Mannington (90%)	Tidal flats, mud flats, floodplains	0-25 cm, roots, peaty with clay, 25-130, organic soup	Very frequently, 0-12.7 cm	0-25.4 cm: silt loam 25.4-61.0 cm: silt loam 61.0-203.2 cm:silty clay loam	7.8 m 4.8 m 7.8 m

Surface Elevation Table (SET)

SET Installation

In August of 2007, 15 Surface Elevation Table (SET) benchmarks were installed at 5 sites (3 SETs/site) along the 50-km Nanticoke salinity gradient. Sites ranged from a mesohaline stretch of wetland near the mouth of the Nanticoke River to tidal freshwater sites near Laurel, Delaware (Figure 2.2). The surface elevation table benchmarks that were installed followed the

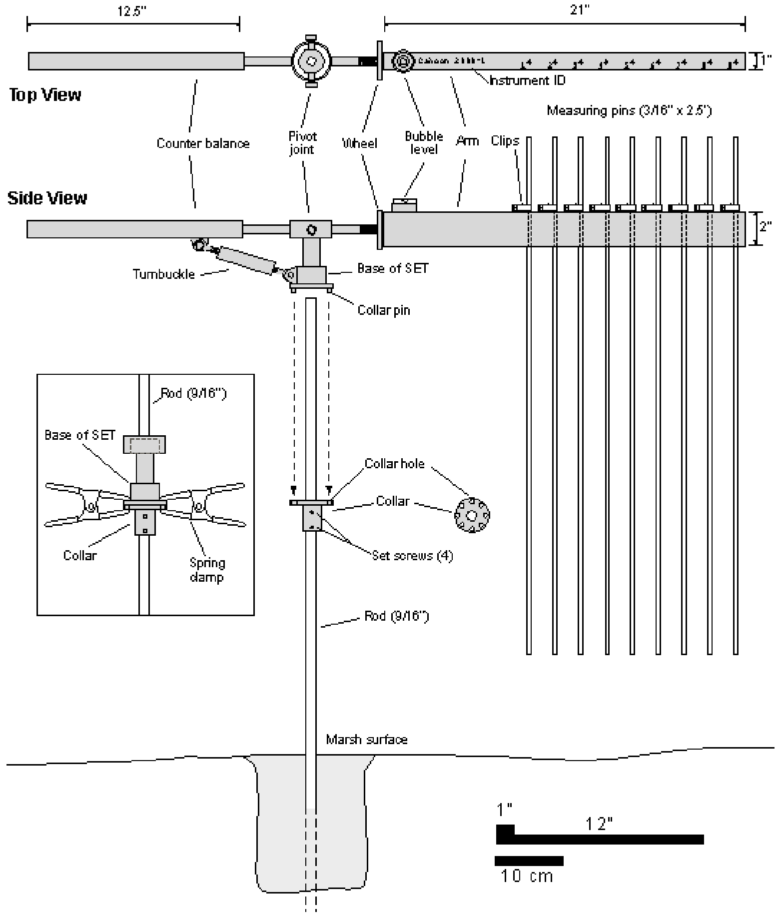

Figure 2.3: Surface Elevation Table (from Cahoon et al. 2002)

Rod-SET design of Don Cahoon and James Lynch of the US Geological Survey (Cahoon et al. 2000, Cahoon et al. 1995, Cahoon et al. 2002). Each SET is comprised of a permanent benchmark and a removable collar that has a rod and 8 position holes around its dial, an aluminum arm with collar pins that locks into the collar holes, and 9 fiberglass pins that are threaded through the arm (Figure 2.3). The collar and arm are removed and used for all 15 of the benchmarks. The SET instrument (measurement arm and collar) were manufactured by Nolan's machine shop in Lafayette, Louisiana.

Before construction, a portable platform was constructed to avoid impacting the area in which the SET would be installed. This was done using 2 plastic Rubbermaid stools, each about 0.3 m high and 0.3 m wide on the bottom to which was bolted a piece of 0.3 m by 0.3 m pressure treated, painted plywood in order to distribute the weight evenly. A 4.6 m section of aluminum bleacher bench was placed between the stools to make a portable boardwalk.

Figure 2.4: Andy Baldwin utilizing pounder slammer to drive in survey rods

SETs were constructed from the boardwalk by first hammering 15.24 cm diameter, 40 cm long PVC pipes with a sharpened end into the marsh surface until a lip of about 15.24 cm stood up from the marsh surface. This PVC pipe protects and anchors the benchmark. Benchmarks were assembled by attaching a stainless steel driving point to 2.54 cm diameter, 1.22 m long threaded stainless steel survey rod sections and driving them into the marsh in the center of the PVC pipe with a sledgehammer. To protect the threads from damage, a stainless steel guard sheath was used, a 2.54 cm thick cylinder with a wider closed end, placed over the survey rod and hit with the sledgehammer. In addition to using a sledgehammer, a pounderslammer was also used, a steel cylinder with a closed end and handles on either side used to drive survey rods. This device eliminates the need to hit the rod on target since about 18 cm of the rod is inside the device when it is lifted and it down on the rod, and it also acts as a protective cap when hammering with the sledge hammer (Figure 2.4).

As each section was hammered into the ground a new section would be screwed on using vice grips to ensure a tight connection. At the deepest site (Site 2), 12 rods were used (14.6 m), at the shallowest site (Site 1) 2 rods were used (2.4 m). The survey rods were driven to a point of refusal, theoretically into the sand strata (pre-submergence subsurface) underneath the highly organic soils of the marsh. The survey rods are driven to the underlying substrate so that the SET measures the deep processes below the root and organic layer in addition to the processes in the organic soil layers. The SET measures processes occurring to the base of the rods and the seasonal shrink-swell of the strata above the bottom of the rods. Point of refusal was determined by the inability of any installation crew member to hammer the rod in a further 1-2 mm more using repeated blows.

Once point of refusal was reached a Dewalt 7-amp cordless angle grinder and 2-18 volt rechargeable batteries were used to cut off the survey rod to be flush with the lip of the PVC pipe. Then the clamp of the receiver, a threaded hollow steel rod with a small notch in it and attached to a clamp by hex bolts, was slipped over the survey rod (Figure 2.5).

Figure 2.5: Benchmark attached to stainless steel survey rod (http://www.pwrc.usgs.gov/set/images/RSET/receiver5.jpg)

Once the receiver was connected to the survey rods, the remainder of the PVC pipe was filled with QuikCrete,™ a quick-setting concrete mix. The concrete was premixed on the boat with water from a large cooler containing fresh water from the lab. Quick-setting concrete will not set well when mixed with salt water so we. After the concrete had been troweled into the PVC pipe, a brass USGS survey marker (identifying the project as research and giving contact info) was placed into the concrete. Once dried, the receiver is cemented firmly into place with the notched receiver rod sticking up roughly 0.3 m from the marsh surface , though the distance from the notched benchmark rod to the surface of the marsh does not need to be measured and it is only important that the distance remains constant (Figure 2.6). The receiver and cement, PVC casing together are the benchmark.

Figure 2.6: Final benchmark with notched receiver rod

Taking the Baseline Measurement

The baseline elevation measurements were taken in October 2007. The temporary platform (the 2 stools and bleacher bench) were set up before measurements were taken as to not impact the elevation measurements, the removable collar was then connected to the receiver. The collar has a rod and 8 holes oriented 45º apart. The collar is welded onto the rod, and the rod has a small steel peg which fits into the notch of the benchmark. The receiver is also fitted with a threaded cap. Once the collar rod is inserted into the hollow receiver pipe, a rubber hammer was used to force the collar peg to the bottom of the receiver notch (Figure 2.7).

Figure 2.7: Inserting receiver peg into benchmark notch

The cap of the receiver was screwed onto the threads of benchmark to ensure a snug fit and to also ensure consistency for all SET measurements. If the receiver were not completely in to the notch, the distance between measuring arm and ground would not be consistent, adding to overall error in the elevation measurements.

Once the collar was in place, 4 of the 8 positions were selected to measure. Positions to measure were chosen based on the orientation of the temporary platform. When installing the SETs, two fiberglass poles were placed in a line to indicate where the stools had been placed and where they would be placed in the future. Stools were placed in line with the poles so that the bench is oriented in the same direction each visit. Positions were then selected based on accessibility from the bench. Once the first position was chosen it determined the other 3 positions to be either the even numbered collar holes or the odd. The 4 positions were chosen to be 90º apart from one another and thus cover the entire collar dial.

After the positions were chosen, the removable measuring arm was put onto the receiver. The removable arm is attached has a collar with two opposite collar pins on the bottom. These pins fit into the collar holes of the receiver (Figure 2.8).

Leveling turnbuckles (Top right

Measuring arm collar

Receiver collar with position

Figure 2.8: Measuring arm being placed on receiver

Figure 2.9: Measuring arm collar with 2 pegs that fit into receiver collar holes, checking distance between aluminum arm and base to maintain same total arm length. In this project distance is 65mm.

The measuring device consists of an aluminum arm with 9 pin holes, a bubble level, and 2 threaded adjustment cyclinders. Once the arm is placed onto the receiver collar, it is held in place not only by the pegs, but also by 2 heavy duty pony clips (Figure 2.10), clamping the receiver collar and the measuring collar together. Once clamped, the fiberglass pins were threaded through the holes and badge clips were used to hold them in place and to prevent them from dropping to the marsh surface. After the pins were placed in the arm, two adjustment cylinders were used to level the arm, measuring it by the bubble level attached to the arm. One leveling device moves the arm up and down and one holds the angle of the aluminum arm in place (Figure 2.8). Because by moving the adjustment cyclinder the total length of the arm can be moved, the distance between the base of the measuring arm and the aluminum arm itself was measured (Figure 2.9). If the total length of the measuring arm were to change, the pins would not fall in the same location, increasing experimental error and giving an inaccurate measurement of elevation change in a very localized location (where the pin falls). It is essential that the pins fall in the exact same location every time you measure, otherwise the readings cannot be compared to one another to determine a rate of elevation change.

Figure 2.10: Pony clips used to hold receiver collar and measuring arm collar together

Pins were then lowered to the marsh surface. When the marsh surface was visible, the pin was lowered and rested on it; however, in many cases dead vegetation covered the marsh surface. If the dead vegetation was already at a state of decomposition so that it resembled part of the soil (leached of color, mostly rotten, broken down, etc.) and was laying flat on the surface, it was considered part of the marsh soil surface and the pin was rested on it; however, if the vegetation was raised from the surface and still had color or firm shape, the pin was lightly twisted until the end either cut through the vegetation or pushed the vegetation out of the way and then rested it on the marsh surface. In the case that the marsh soil surface was inundated or extremely silty so that what appeared to be the surface could not hold the weight of the pin, the pin gently rested on the surface that was slightly firmer.

After placing each pin, it was prevented from sinking into the marsh surface with a badge clip placed on the pin and resting on the top of the aluminum arm. Once all of the pins were in place the distance from the top of the arm to the top of the pin was measured. The base of a metal meter stick was placed against the badge clip and lined the pin up on the ruler. This creates a very slight triangle since the width of the badge clip prevented the pin from lining up completely straight with the ruler, so the badge clips were all oriented in the same way so that the added distance would remain constant each time pins were measured decreasing the error of the added badge clip width. As long as the measurements are consistent, they are relative to each other. If the width of the badge clip is always incorporated in measurement then it eliminates it from the elevation change measurements because the measurements are of relative change rather than absolute, the width of the badge clip will always remain constant so when you compare the pin measurement to the original baseline pin measurement, both have the width of the badge clip in them, so the amount of change is due only to the elevation change. The SET is fairly accurate (accuracy is ± 1.5 mm , Boumans and Day 1993) in measuring localized elevation change .

The baseline readings are the measurements by which all subsequent pin measurements are compared. After the baseline was established in October 2007, the first set of elevation change measurements were taken in April 2008, another set in October 2008, and most recently, a set in April 2009. Measurements taken in October and April reflect seasonal dynamics. In October, most of the summer growth vegetation has collapsed or is collapsing, and in April, most of the vegetation has been broken down after the winter period and the new vegetation is just beginning to come up. Semi-annual measurements reflect not only rates of annual elevation change but also the seasonal elevation change dynamics.

Data Analysis

For each SET, there are 4 positions with 9 pin readings at each position. The difference of each pin reading over time was taken. For example, the value at pin 9 in position 4 of October 2007, the baseline, was subtracted from the value at pin 9, position 4 of April 2008. This value is equal to the elevation change from October 07-April 09. Each time a new set of pin measurements was taken, the baseline values were subtracted from the newly recorded values. The 9 pin differences for each position were then averaged for a mean elevation change for each position; for example, pin differences 1-9 for position 4 of SET4A were averaged. The means of the positions were then averaged, the pin mean from position 4,6,8, etc. to get total mean for the SET at that location (e.g. 2A, 2B, 2C). Elevation changes were plotted over time. Once plotted, a simple linear regression (forced through the origin; i.e., day 0) for each SET curve was done to identify the overall trend of the data (e.g. elevation rising or sinking). The slopes of the regression lines, which represented the rate of elevation change per day, were taken and multiplied by 365 for the annual rate of elevation change (mm/year). The 3 replicate slope values were averaged for each SET (e.g. 4A, 4B, 4C) and then an ANOVA between the slope means of the 5 SET sites was conducted. The sites were grouped by salinity regime [fresh, oligohaline and mesohaline, Tukey means separation procedure used according to the Cowardin et al. (1979) salinity modifiers] and ran an ANOVA on the slope means between the 3 salinity regime types.

Marker Horizon

Figure 2.11: Andy Baldwin laying feldspar powder marker horizon plots

To measure accretion rates, feldspar marker horizon plots were utilized.

Creating the plots

In October 2007 while SET baseline readings were taken, marker horizon (MH) plots were laid. 3 plots per SET were laid. A 0.25m^2 frame was constructed from 2.54 cm diameter PVC and feldspar clay powder was dusted approximately 2 cm thick inside the frame to create a 0.5 m^2 plot (Figure 2.11). Plots were laid parallel to the bench platform on the other side of the SET.

In April 2008 the first accretion measurements were taken. To take an accretion core, a liquid nitrogen Dewar container (purchased from Cryofab Inc., Kenilworth, NJ) was used, a transfer hose, a nozzle, and a bullet tipped copper sheath. This system is used to prevent compaction when the feldspar core is removed, also known as a “marshsicle” or “frozen finger”. The first step is to insert vertically a copper tube that has an empty bullet tip welded to the end of it (Figure 2.12). The copper sheath is 0.95 cm in diameter and hollow. The tube was cut into 25 cm lengths and inserted into the ground about 20 cm with about 5 cm protruding from the feldspar plot. The nozzle of the tank is then inserted into the copper sheath. The nozzle is 0.32 cm diameter copper tubing (Figure 2.12).

Figure 2.12: Outer sheath and inner nozzle used for taking MH cores

The nozzle is attached to a braided steel hose that is attached to a liquid nitrogen Dewar (15L tank) (Figure 2.13). When the valve on the dewar is opened, liquid nitrogen cools the hose down and once the hose has cooled begins to fill the copper sheath freezing the marsh soil to the outer side (Figure 2.13).

Figure 2.13: Filling copper sheath with liquid nitrogen

After liquid nitrogen droplets begin coming out of the sheath, the liquid nitrogen should run for another 2-3 minutes before turning the valve off. The nozzle was then removed from the sheath. The frozen core was cut out using a knife. The marsh soil was frozen to the copper sheath. To get a clean surface, the side of the core was scraped in order to find the feldspar layer (Figure 2.14.A).

Figure 2.14: A. Marker horizon core with feldspar layer B. Measuring accretion using vernier caliper

feldspar layer to the top of the soil layer (Figure 2.14.B), making sure not to measure any frozen surface water. The average of these two measurements is the amount of accretion from October 2007-April 2008.

Methodology Revised

A 15L liquid nitrogen Dewar when full weighs 45kg (100lbs) and very cumbersome to carry through the marsh. A new method was needed to make the process more efficient. The newly developed system used a 1L plastic Nalgene "squeeze" bottle with a lid and a nozzle and a thin (0.32 cm diameter) rubber tube. As liquid nitrogen is exposed to ambient air temperatures, it changes from a liquid to a gas very quickly. The bottle was filled with liquid nitrogen about ¼ of the way from the 15L dewar that was kept on the boat. The bottle was carried without a lid on it in a 18.9 liter plastic bucket to the feldspar plot. The copper sheath was inserted into the feldspar plot vertically (Figure 2.15) and then attached the rubber tube to the nozzle of the plastic bottle and the other end of the rubber tube was inserted into the copper sheath which was placed in the feldspar plot as described above (Figure 2.16).

The lid of the plastic bottle was screwed on creating a self-pressurizing system (Figure 2.17).

Figure 2.15: Placing bullet-tipped copper sheath in plot

Figure 2.16: Inserting rubber tube into sheath

Figure 2.17: Self pressurizing system for MH cores

As the liquid nitrogen warmed it created pressure inside the bottle and forced the liquid out through the nozzle through the rubber tube and into the bullet tipped sheath to create a marsh soil core. The soil cores created by this method used less liquid nitrogen, were more evenly and consistently shaped, and required less than 2 kg (3 lbs) to carry.

Data Analysis

A core was taken at each SET (15 cores total) and two accretion measurements were read from each core. The 2 accretion measurements from each core were then averaged to get a mean amount of accretion at each SET. The accretion over time was plotted and a simple linear regression was done on each accretion curve. The slopes and multiplied them by 365 to get a rate of accretion per year (mm/year). The average of the slopes of the three replicates were taken for the mean amount of accretion at each site (e.g. 4A,4B,4C) per year. An ANOVA was conducted on the mean slopes of the 5 sites. The sites were grouped by salinity regime and an ANOVA was done on the mean slopes between the three salinity types (fresh, oligohaline and mesohaline). Sites 1 and 2 were mesohaline, Sites 3 and 4 were oligohaline, and Site 5 was fresh.

Salinity

Measurements of water salinity in the channel bordering each site were taken using a YSI conductivity meter (YSI, Yellow Springs, OH).

Data Analysis

All salinity measurements for each site taken from 2007-2009 were averaged measurements from each of the 3 replicates were included in the mean for each site.

PATUXENT EXPERIMENTAL STUDY

To test the effects of sea level rise on tidal freshwater marshes an experiment was created at the Patuxent River. Saltwater intrusion associated with sea level rise was simulated and the impacts on the vegetation of the marsh were observed. The infrastructure to monitor the effect of salinity treatments on surface elevation in the future was developed, also.

Hypothesis

There will be a change in the vegetation communities in the plots irrigated with saline solution; specifically, more vegetation dieback and possibly colonization by more salt-tolerant species.

Study Site

The Patuxent River is a major tributary to the Chesapeake Bay (Figure 2.18). Jug Bay, a wetland preserve, is 68 km from the mouth of the river. It is located where Western Branch and Patuxent River flow together forming a large tidal freshwater marsh between these two rivers. This area is considered a Nationally Important Bird Area by the American Bird Conservancy and is a rich marsh area with high biological diversity of macrophytic vegetation (Wikipedia.org 2009). Billingsley Marsh is a large marsh at the confluence of

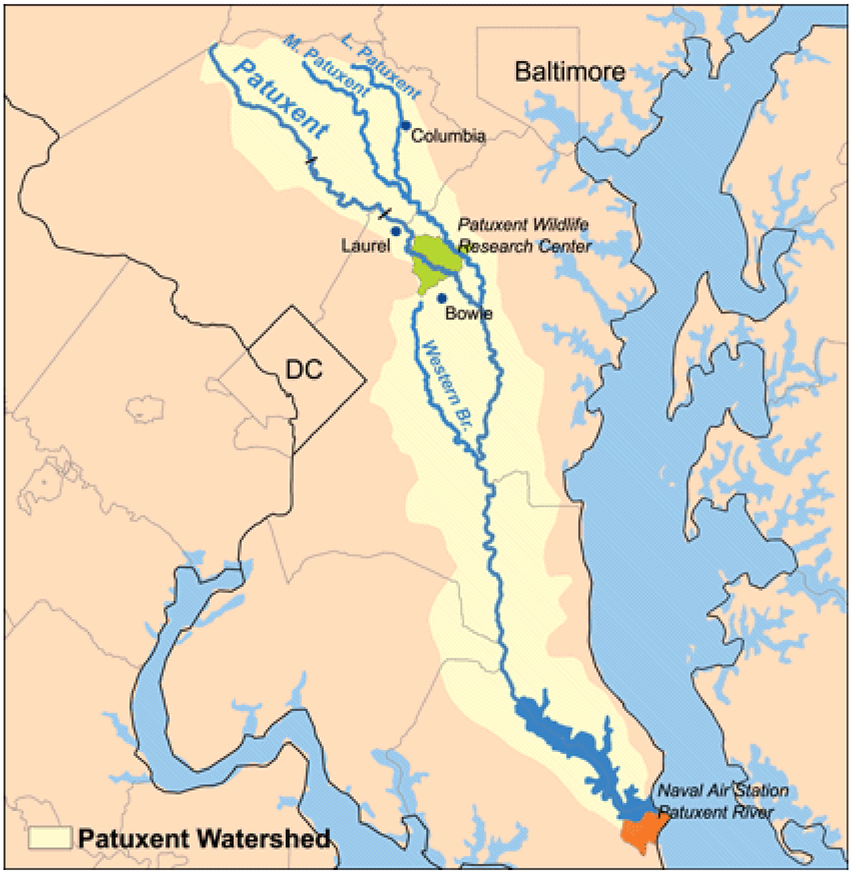

Figure 2.18: Patuxent River Watershed, red circle indicates study area (http://en.wikipedia.org/wiki/File:Patuxentrivermap.png)

Western Branch and the Patuxent River.

Experimental Design

5 sets of quadrats were set up in Billingsley Marsh with 2 paired quadrats per SET station. Each of the 5, 2-quadrat sets has 1 quadrat acting as the control and 1 quadrat receiving salinity treatment. The SET stations are numbered 1-5 and the quadrat locations are described as either salt or fresh.

Salinity Treatment

For each of the 10 plots a drip irrigation system was constructed to deliver treatment solutions. Each system was comprised of a 71.1 cm x 114.3 cm- 378.5 liter black polyethylene tank with a bulkhead fitting and a lid, a stand, and the tube delivery system. The stands were constructed out of pressure treated lumber (Figure 2.19). The stands had 3.04 m legs and 2-2.54 cm thick plywood platforms: one to hold up the tank, and one to act as the base that sits on the marsh surface and keeps it from sinking in. The legs go into the marsh about 1.2 m to anchor it in and to keep the stand from being washed away. The tank sits on the upper platform and is held in place by 5 cm x 10 cm boards that frame the top. From the tank a tube system was attached. Black UV-Resistant Tygon™ tubing was used, 2.54 cm outer diameter, 1.9 cm inner diameter. Black was used to decrease the rate of algal growth inside the tube. The Tygon™ tubing attached to a needle valve that was

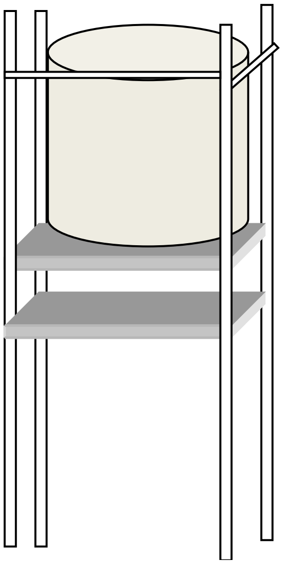

Figure 2.19: Irrigation barrels and stand

attached to the bulkhead fitting, but the needles valves were removed due to biofilm and invertebrate clogs (Figure 2.20), and replaced them with plastic T's that are attached to the bulkhead fitting by tubing.

The tubing branches twice. There are 4 ends that have a 1.9 cm inner diameter, 30.48 cm long permeable recycled rubber soaker hose attached. The soaker hoses are capped with end plugs. The soaker hoses deliver the treatment slowly. The system is gravity fed and relies on the pressure of the elevated tanks to push the water through the system to 4 locations in the plot (Figure 2.21).

Figure 2.20: Removing invertebrate clog from needle valve

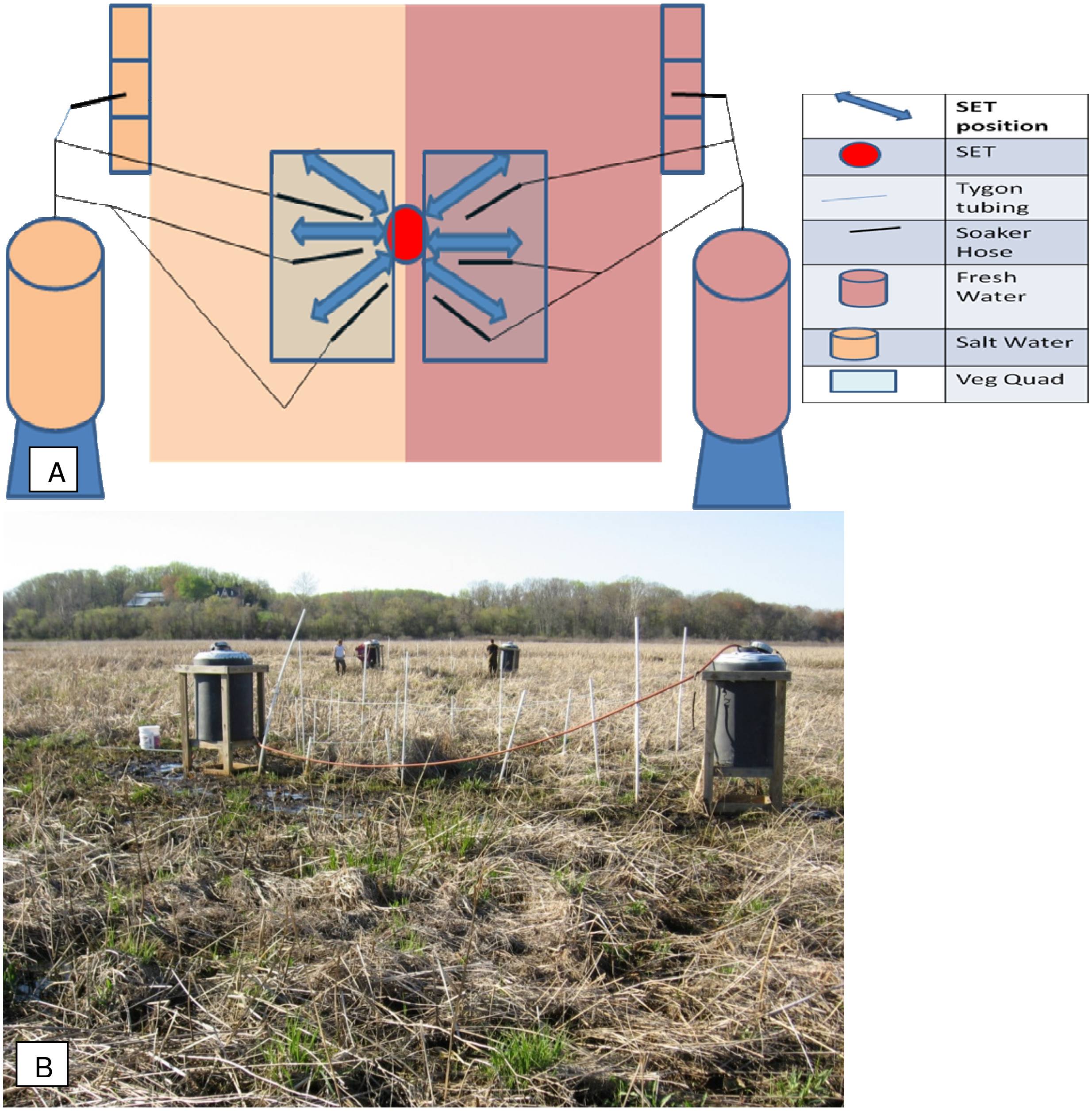

Figure 2.21: (A) Experimental Set Up at Patuxent B. (B)Filling barrels

The soaker hoses are staked in the plot with small plastic lawn stakes. In the center of the plot plastic lawn edging: 8 cm subsurface, 2.54 cm above surface, was hammered in to discourage treatment bleed over between the plots (Figure 2.22).

Barrel tops were spray painted white to reduce the internal temperature in the barrels and to be able to see them better from a distance.

A Note about SETs

Originally, the set up was designed to measure the effect of saltwater intrusion on marsh elevation. In the center of each quadrat is an SET benchmark, as described above, and the 30.48 cm soaker hoses are staked along the positions of the SET arm in order to measure elevation change exactly where the treatment is delivered. The baseline measurement was taken before treatment application began in June of 2009; however, subsequent elevation measurements have not yet been taken due to irrigation system malfunctioning. Baseline measurements are not presented in this paper since without

Figure 2.22: Scott Allen hammering in lawn edging to prevent treatment overlap.

subsequent elevation measurements, the baseline measurements are not relevant data.

Salinity Treatment

To simulate saltwater intrusion, plots were treated with salt water. Instant Ocean, a synthetic ocean salt mix sold for salt water aquariums that contains sulfate and common salts present in sea water, was used as treatment. To create the treatment a gas-powered Honda pump was used to pump channel water through a garden hose (on average 90 m of garden hose ran from the river to the treatment plots) into the 378.5 liter (100 gal) barrels. At each plot 1 barrel was randomly assigned to the control treatment, (plain river water), and 1 barrel to the salinity treatment, (channel water with Instant Ocean mixed in). Treatments began in July 2008 with 1ppt salinity. It was increased two weeks later to 2ppt, and finally to 5ppt 3 weeks after that. Treatments were planned to achieve a salinity of 5 ppt in the top 10 cm of soil in an area surrounding the soaker hoses, a plot of approximately 1 m x 2 m measured 1 week post treatment. Application of treatments was through a trial and error approach in order to raise the soil salinity to approximately 5 ppt. Treatments were applied five times (Table 2.2).

Date	Treatment (ppt)
8.4.08	1
8.27.08	2
3.17.09	5
3.27.09	10
4.17.09	13

Table 2.2: Dates and level of salinity treatments added to barrels at Patuxent

The treatment took a few days to drain from the barrels. Porewater salinity was measured utilizing soil sippers and a YSI conductivity meter. Soil sippers are small Teflon tubes with small holes drilled throughout their lengths (Figure 2.23).

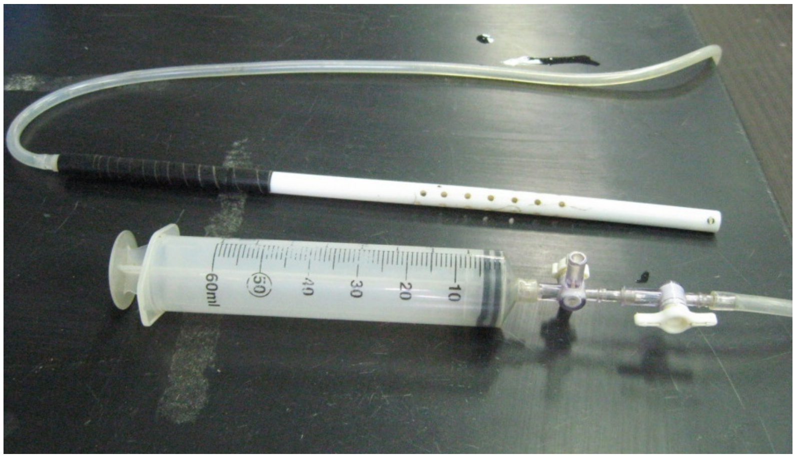

Figure 2.23: Soil sipper, Teflon tube is inserted into ground and syringe is used to pull porewater out

They are sealed on one end with silicone calk and the other end is attached to a rubber tube. The rubber tube attaches to a plastic syringe.

Sippers were inserted to a depth of 10cm into irrigated plots next to the soaker hoses. A syringe was then used to draw out soil porewater. Once the syringe was filled with porewater, a conductivity probe was dropped into the syringe to determine the salinity of the porewater.

The following treatments were done in the spring of 2009 beginning in April. Treatments were started at 5ppt and increased every two weeks by 5ppt finally reaching 15ppt. Porewater salinity was measured every 2-3 weeks through April and part of May 2009.

Vegetation Monitoring

To determine whether the salinity treatments were affecting vegetation, two vegetation studies were done. A baseline vegetation survey was conducted in July 2008 and a seedling recruitment study was done in April 2009.

Baseline Vegetation Survey

Measurements

At each plot a $2.5m^2$ quadrat was monitored. Quadrats were placed to include ¾ soaker hose locations. In the quadrat each species was identified and estimated a cover class for that species.

Data Analysis

For the vegetation data the midpoints of the cover classes were used to determine total cover for each plot and mean percent cover for each species per plot. This survey was done before treatment was applied so all plots were replicates of one another.

Seedling Recruitment Study

In April 2008, at each plot a 30.48 cm diameter circlular quadrat was monitored surrounding each rep (soaker hose). In the quadrat seedlings and resprouts were identified by species and counted (Figure 2.24).

Figure 2.24: Seedling recruitment study, counting and identifying seedlings in

Seedling Data Analysis

For each replicate the number of resprouts and seedlings were totaled. The number of species at each replicate was also totaled. The mean of the three replicates was then taken to get a mean number of resprouts and seedlings in each plot, and also the mean of the number of species of seedlings and the number of species of resprout for each plot were taken. Paired t-tests were done comparing the total number of seedlings, resprouts, seedlings and resprouts, number of species of seedlings and resprouts, number of species of seedlings and number of species of resprouts in each treatment group (salt and fresh). The 5 quadrats served as blocks containing 1 salt plot and 1 fresh plot. The first set of t-tests was conducted including all of the 5 quadrats. The second set of t-tests that were conducted excluded quadrats in which at least 1 of the irrigation systems had not functioned properly. When the irrigation systems got clogged, no treatment was delivered to the plot so these were removed from analysis. An alpha level of 0.10 was used based on the environmental analyses. Ecological studies done in the field use an alpha level of 0.10 due to the large environmental noise and high variability of sites.

III. RESULTS

NANTICOKE RIVER OBSERVATIONAL STUDY RESULTS

The Nanticoke estuary has salinities ranging from as high as 22 ppt measured at Site 1 to 0.1ppt at Site 5. Site 1 had the highest salinities, and salinity level consistently decreased moving upstream from Site 1 to Site 5 (Figure 3.1).

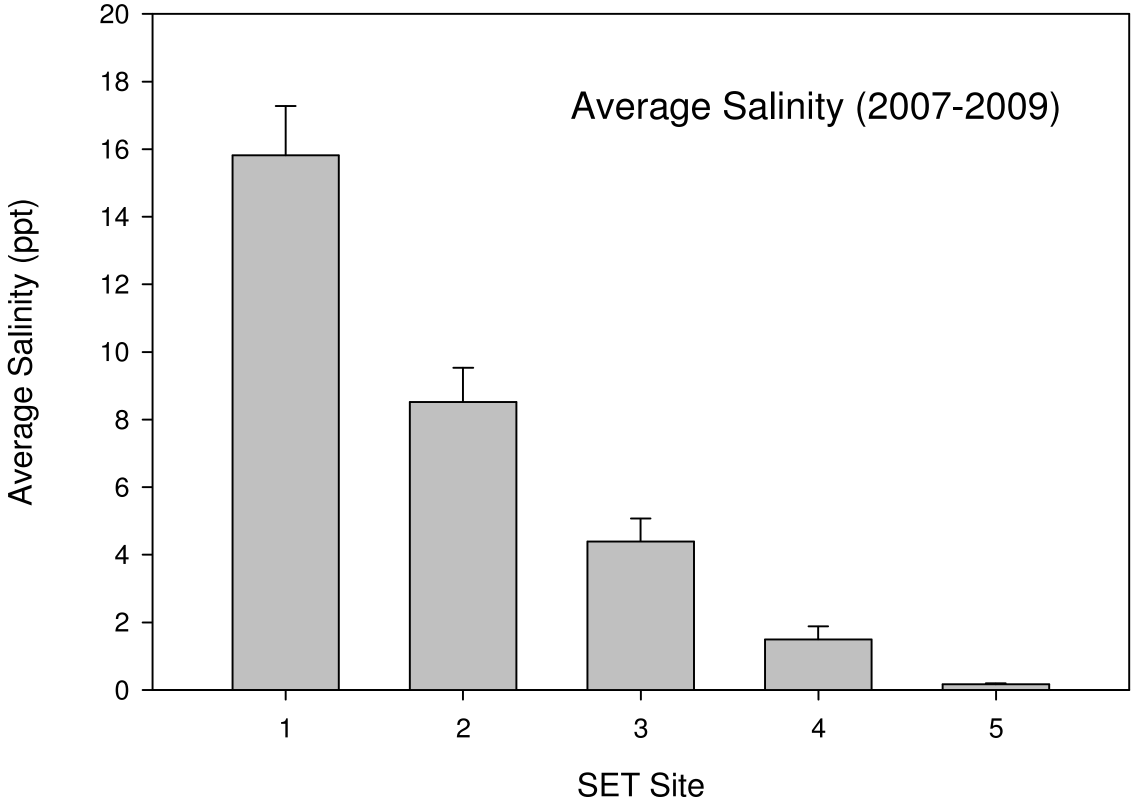

Figure 3.1: Mean Salinity of SET sites +1 SE along 50km gradient of Nanticoke River over 2 years. Site locations are shown in Figure 2.2.

An Analysis of Variance done between the 5 sites on the mean rates of change of elevation and accretion reflected that on a site-by-site basis, there were no significant differences between the sites (Figure 3.2). This was due to considerable variability between replicate SETs within each site (Figure 3.3 and Table 3.1). Site 1, a mesohaline site with an average salinity of 16 ± 1.46ppt (Figure 3.1), had the only positive elevation increase across 3 replicate SETs between October 2007-April 2009, increasing approximately 1mm/yr (Figure 3.2). Site 3, an oligohaline site, had the greatest elevation decrease; decreasing nearly 20 mm/ year between October 2007–April 2009, followed by Site 4, which also had a comparatively high rate of elevation decrease, about 13mm/year (Figure 3.2).

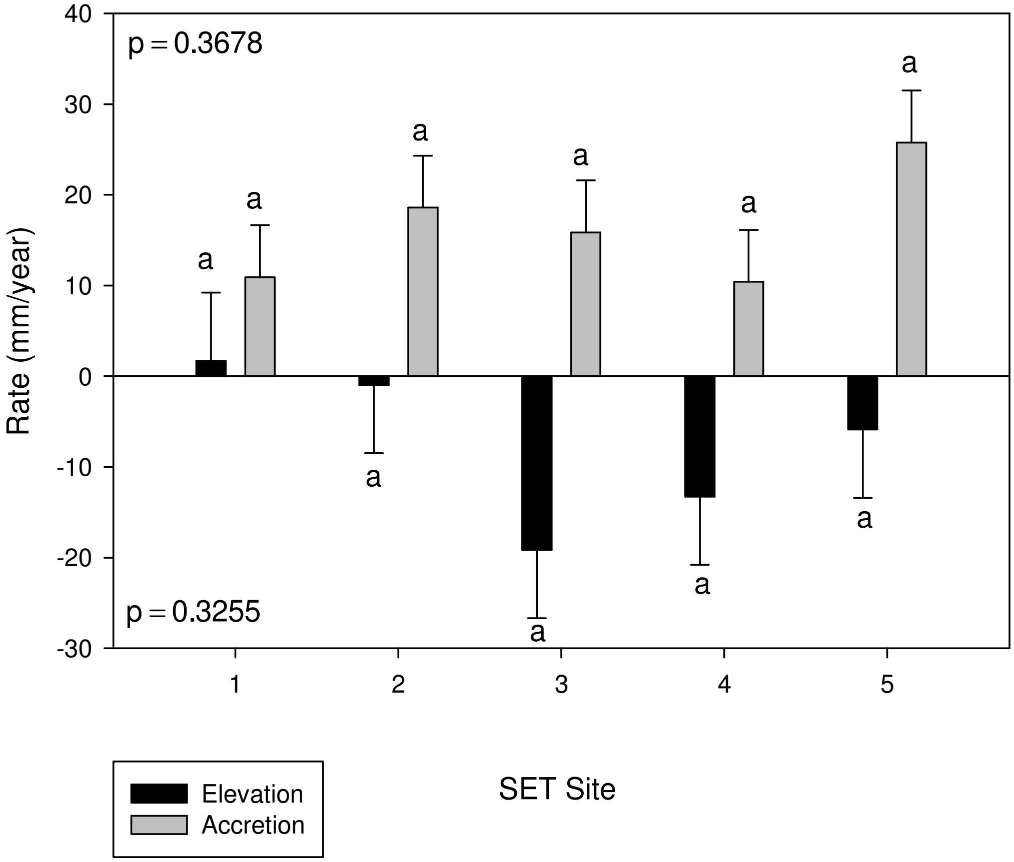

Figure 3.2: Mean rate of elevation and accretion change ± SE at each site, results of Analysis of Variance of rates of change and p-value (Bottom left, p-value for elevation change rate, Top left, p-value for accretion).Within elevation or accretion, means that were significantly different at a p-level of 0.1 (Tukey test) are indicated by different lower case letters

Site 1 had positive elevation change that was significantly different from zero at 2 of 3 replicates and was the only site that increased in overall elevation (Figure 3.3). Accretion and elevation measurements vary seasonally. Accretion patterns reflect a dramatic increase from April 2008-October 2008, followed by a decrease from October 2008-April 2009. It appears that rates of accretion are higher in October, most likely due to the senescence of the vegetation, followed by a drop in accretion, most likely due to vegetation compaction and decomposition during the winter months (Figure 3.3). Elevation patterns reflect that elevation at many sites drops from April to October (encompassing the growing season) and increases from October to April (winter months), most likely because of water removal and transpiration during the growing season compacting the soils and a lower rate of evapotranspiration during the winter months (Figure 3.3).

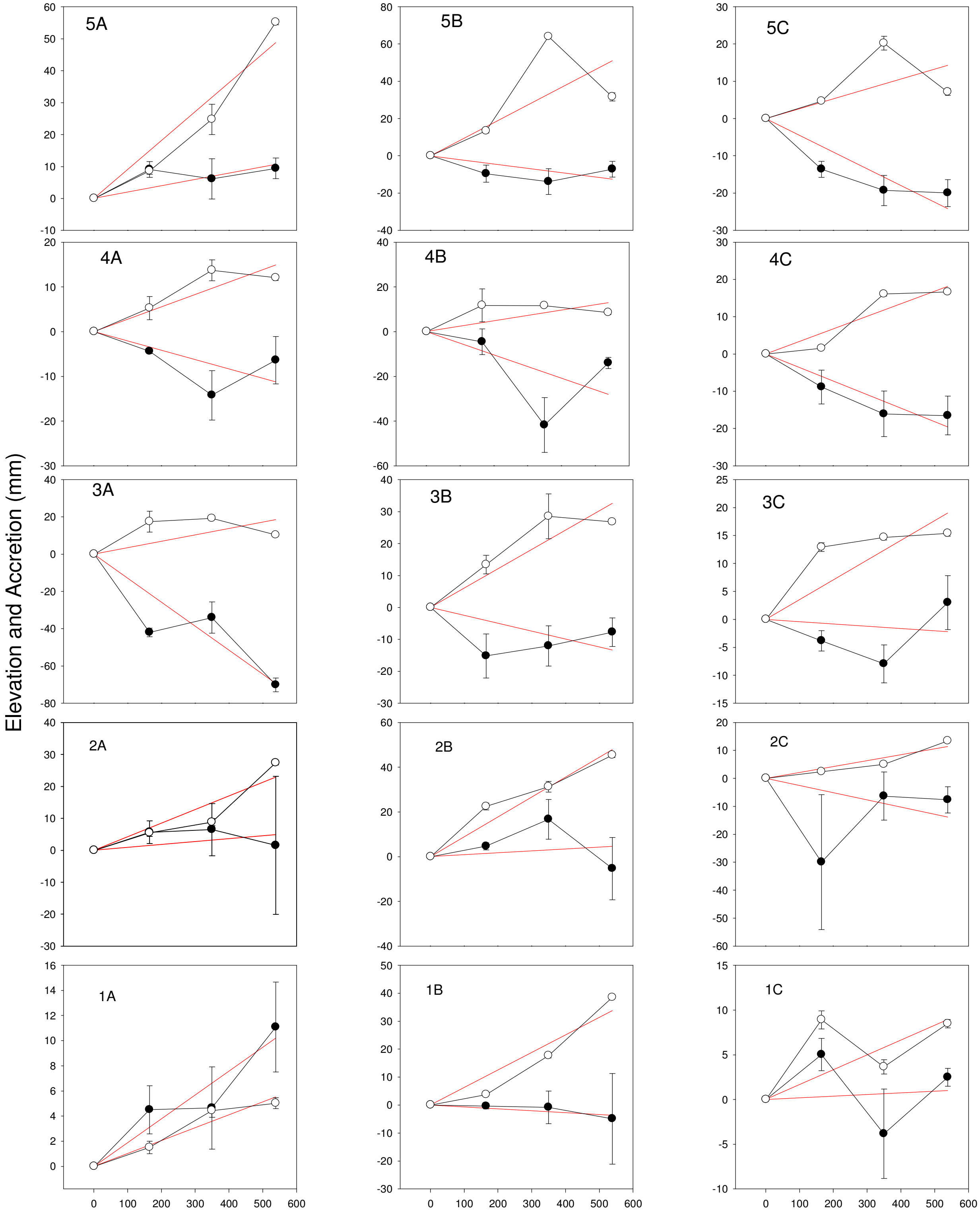

Figure 3.3: Elevation and Accretion Change along Nanticoke Estuary, October 2007-April 2009. The x-axis shows number of days since the baseline reading in October 2007. The sites are arranged in order proceeding downstream from Site 5 to Site 1. Plotted values are mean + SE (n=4 for elevation, n=2 for accretion).

Elevation ●

Accretion ○

Table 3.1 reflects the results of simple linear regression for each parameter, elevation and accretion, at each SET site (1-5, A-C). Site 2 had annual rates of elevation change that were not significantly different from zero-- the total elevation change remained flat during the study period (Table 3.1). R^2 values were higher overall for accretion measurements compared to elevation measurements. Positive accretion differed significantly from zero and Sites 3,4, and 5 had negative overall elevation change that was significantly different from zero (Table 3.1).

Table 3.1: Elevation and Accretion Change along the Nanticoke Estuary over time (October 2007-April 2009) and Regression Results of Each Line. P-values are for regression lines

Parameter	**Site**	**Rep**	**Slope (mm/day)**	**Rate of Change (mm/year)**	**Pr>|t|**	**R-Square**
accretion	1	A	0.0102	3.7	0.0013	0.98
	1	B	0.0627	22.9	0.0042	0.95
	1	C	0.0166	6.1	0.0617	0.74
	2	A	0.0425	15.5	0.0079	0.93
	2	B	0.0889	32.4	0.0011	0.98
	2	C	0.0212	7.7	0.0052	0.95
	3	A	0.0343	12.5	0.0913	0.67
	3	B	0.0604	22.0	0.0061	0.94
	3	C	0.0354	12.9	0.0163	0.89
	4	A	0.0276	10.1	0.0078	0.93
	4	B	0.0240	8.8	0.062	0.74
	4	C	0.0337	12.3	0.0078	0.93
	5	A	0.0904	33.0	0.0028	0.97
	5	B	0.0946	34.5	0.0588	0.75
	5	C	0.0266	9.7	0.102	0.64
elevation	1	A	0.0189	7.0	0.0035	0.96
	1	B	-0.0068	-2.5	0.0348	0.82
	1	C	0.0019	0.7	0.7694	0.03
	2	A	0.0091	3.3	0.1949	0.48
	2	B	0.0085	3.1	0.6112	0.10
	2	C	-0.0256	-9.4	0.3483	0.29
	3	A	-0.1287	-47.0	0.0081	0.93
	3	B	-0.0248	-9.0	0.1146	0.62
	3	C	-0.0041	-1.5	0.6354	0.08
	4	A	-0.0208	-7.6	0.0675	0.72
	4	B	-0.0521	-19.0	0.1195	0.61
	4	C	-0.0363	-13.3	0.0044	0.95
	5	A	0.0197	7.2	0.0327	0.83
	5	B	-0.0233	-8.5	0.0701	0.72
	5	C	-0.0449	-16.4	0.0084	0.93

Although there were no significant differences in elevation and accretion when compared between individual sites, when sites were grouped and analyzed based on salinity regime using salinity modifiers of Cowardin et al (1979), there were significant differences between the rates of elevation change in the oligohaline marshes (mean salinity of 0.5-5ppt) compared to the mesohaline marshes(salinity 5-18ppt) (p=0.097). The fresh marshes (salinity <0.5ppt) included Site 5, oligohaline were sites 3 and 4, and mesohaline sites were Sites 1 and 2. Oligohaline marshes had a significantly higher rate of elevation decrease compared to the mesohaline marshes; however, neither the mesohaline nor the oligohaline were significantly different from the fresh marshes at a p-level of 0.1 (Figure 3.4).

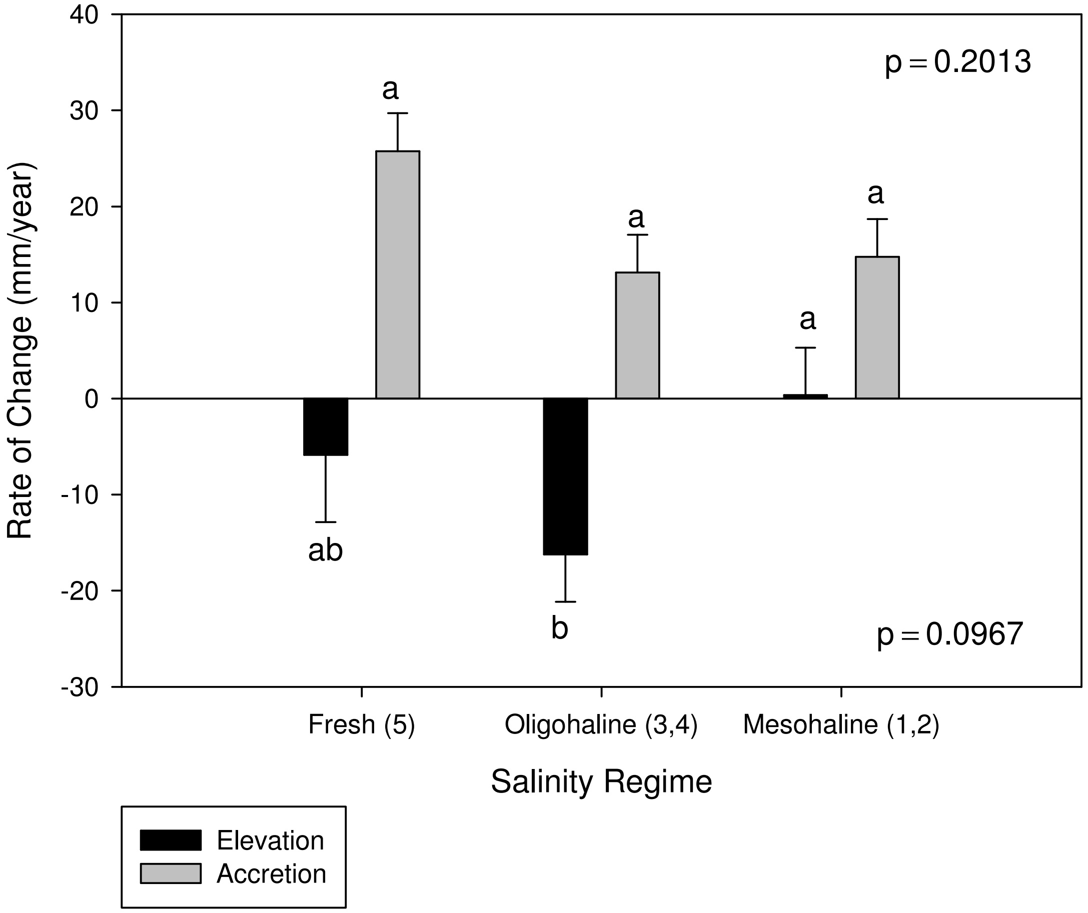

Figure 3.4: Mean rates of change +SE or –SE for negative values based on salinity regime and results of Analysis of Variance between elevation and accretion rates. P-values for ANOVA: Top Right p-value is for accretion, Bottom Right p-value is for elevation change.Within elevation or accretion, means with different letters are significantly different (p<0.1, Tukey test). Fresh sites include Site 5. Oligohaline sites include Sites 3 and 4. Salt sites include Sites 1 and 2.

Accretion rates were not significantly different between salinity regimes (p=0.20).

PATUXENT RIVER EXPERIMENTAL STUDY RESULTS

The overall salinity of the Patuxent experimental plots before treatment was 0.2ppt. Salt irrigation had a significant effect on porewater salinities measured at 10cm depth 2-4 weeks after treatment application. Salt plots had a significantly higher salinity (p=0.034) with a mean of 1.9 ± 0.04 ppt compared to the fresh plots, which had a mean of 0.3 ± 0.51 ppt (Figure 3.5).

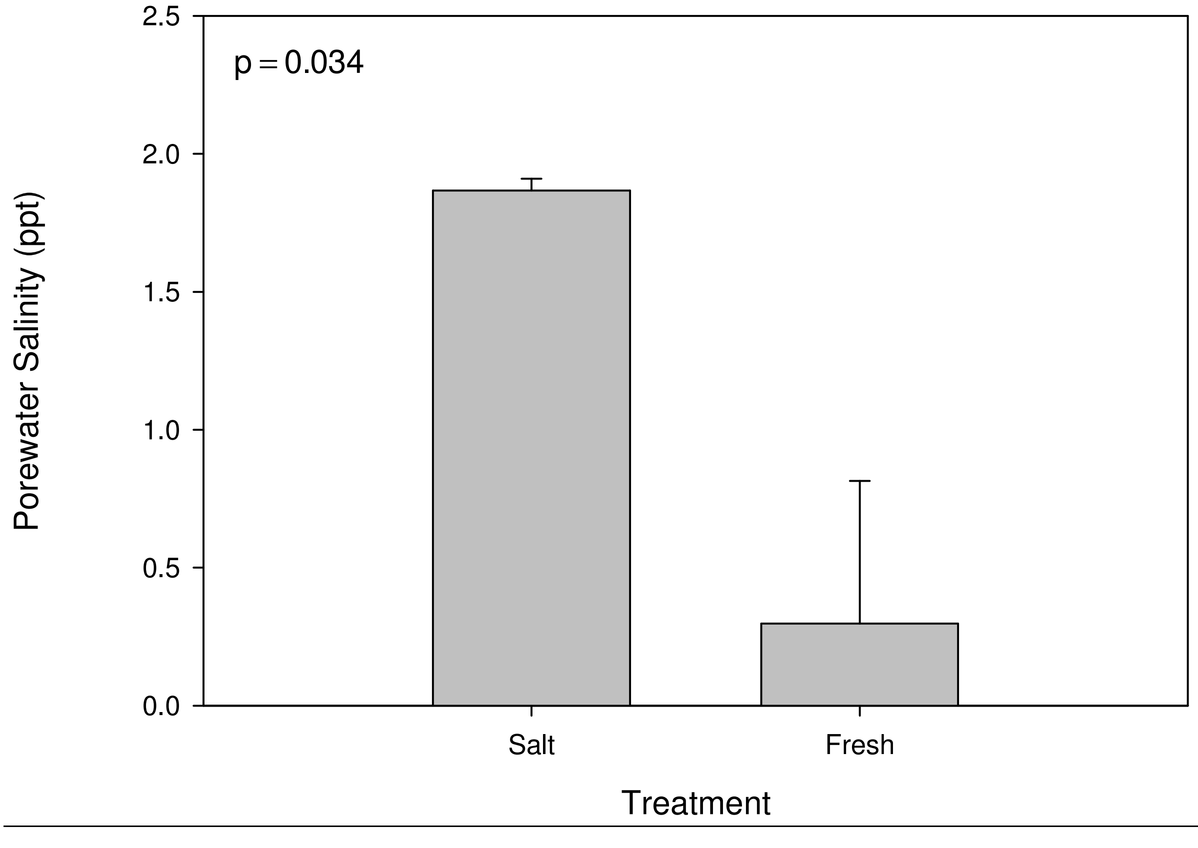

Figure 3.5: Mean porewater salinities +SE (n=5) taken at 10cm depths 2-4 weeks post treatment application at each Patuxent replicate position and averaged for overall treatment means. P-value of paired t-test between means shown in the upper left, t-crit=1.86, 8 df.

Salinities varied after each treatment (Table 3.2). In some cases, salinity was residual in the soil profile; however, in some cases, porewater salinities do not reflect treatment. High variability was due to clogging problems during early operation of irrigation system.

Table 3.2: Raw porewater salinities measured 2-4 weeks post treatment application including data from malfunctioning irrigation systems (1W and 3W). A-C are replicate SET positions, F represents thefeldspar marker horizon plot.

				Date	
Plot	**Treatment**	**Subplot**	**3.27.09**	**4.17.09**	**5.1.09**
1E	fresh	A	0.2	0.2	0.2
1E	fresh	B	0.2	0.2	0.2
1E	fresh	C	0.2	0.2	0.2
1E	fresh	F	0.2	0.2	0.2
1W	salt	A	0.2	0.2	3.4
1W	salt	B	0.2	0.2	2.4
1W	salt	C	0.2	0.2	4.5
1W	salt	F	0.2	0.2	2.1
2E	salt	A	1.2	0.4	1.8
2E	salt	B	0.5	0.4	4.2
2E	salt	C	0.7	5.5	0.3
2E	salt	F	0.5	5.6	5.6
2W	fresh	A	0.3	0.3	0.7
2W	fresh	B	0.4	0.3	0.4
2W	fresh	C	0.4	0.2	0.7
2W	fresh	F	0.2	0.2	0.2
3E	fresh	A	0.2	0.2	0.2
3E	fresh	B	0.2	0.2	0.2
3E	fresh	C	0.2	0.2	0.2
3E	fresh	F	0.2	0.2	0.2
3W	salt	A	2.2	1.4	1.2
3W	salt	B	1.3	3.7	5.8
3W	salt	C	0.3	1	2.5
3W	salt	F	0.5	2	2.6
4E	fresh	A	0.3	0.3	0.8
4E	fresh	B	0.3	0.3	0.5
4E	fresh	C	0.3	0.3	0.8
4E	fresh	F	0.3	0.3	0.5
4W	salt	A	13.3	0.7	1.7
4W	salt	B	1.2	0.3	4.5
4W	salt	C	3.4	0.3	0.8
4W	salt	F	2.5	4.3	8.8
5E	fresh	A	0.4	0.3	0.2
5E	fresh	B	0.5	0.3	0.2
5E	fresh	C	0.3	0.3	0.4
5E	fresh	F	0.3	0.2	0.3
5W	salt	A	0.3	0.3	0.3
5W	salt	B	0.4	0.3	0.7
5W	salt	C	1.5	0.2	0.2
5W	salt	F	0.3	0.2	0.3

Seedling Survey

Table 3.3 reflects paired t-test results including all plots at each of the 5 Patuxent sites. The mean number or seedlings species in each salt-treated plot was 2.6 ±0.48 compared to 3.7±0.33. Table 3.4 reflects the results of paired t-tests after taking out of the data the plots in which the irrigation systems did not deliver treatment. There were significantly more seedlings in the fresh-irrigated plots than in the salt plots (p=0.0634) (Table 3.4).

Table 3.3: Results of paired t-tests comparing all fresh plots to salt plots

Parameter	**DF**	**t-crit**	**p-value**
Mean Total Resprouts and Seedlings	4	0.55	0.6111
Mean Total Resprouts	4	-0.72	0.5137
Mean Total Seedlings	4	0.69	0.5282
Mean Number Species Resprouts and Seedlings	4	-0.77	0.4859
Mean Number Species Resprouts	4	-1.20	0.298
Mean Number Species Seedlings	4	-0.0	1

Table 3.4: Results of paired t-test comparing fresh to salt plots not including malfunctioning irrigation systems (reps 1 and 3)

Parameter	**DF**	**t**	**p-value**
Mean Total Resprouts and Seedlings	2	1.45	0.2852
Mean Total Resprouts	2	-0.52	0.6534
Mean Total Seedlings	2	1.85	0.206
Mean Number Species Resprouts and Seedlings	2	0.45	0.6968
Mean Number Species Resprouts	2	-0.67	0.5736
Mean Number Species Seedlings	2	3.78	0.0634

Vegetation Survey

The most common species at the Patuxent experimental plots in the summer (July) of 2008 was *Peltandra virginica*, which covered on about 30% of each vegetation quadrat (Table 3.5). The second most dominant species based on percent cover was *Impatiens capensis*, which was also the most prominent species of seedling in April 2009. There were on average 104±14.2 individual *Impatiens capensis* seedlings at each of the 5 Patuxent experimental SETs.

Table 3.5: Vegetation species and mean percent cover per 2.5m plot at Patuxent SET sites, July 2008

Species	Mean % Cover/ 2.5m plot	SE
Bidens laevis	7.9	3.59
Bidens species	0.1	0.05
Carex lacustris	0.5	0.38
Cicuta maculata	2.4	1.34
Cuscuta gronovii	0.1	0.04
Galium tinctorium	1.1	0.69
Impatiens capensis	17.6	11.46
Leersia oryzoides	51	22.95
Mentha arvensis	2.6	1.92
Mikania scandens	0.6	0.41
Murdannia keisak	11.3	4.92
Nuphar lutea	9.5	4.03
Peltandra virginica	30.4	15.8
Pilea pumila	8.3	4.26
Polygonum arifolium	12.7	5.88
Polygonum punctatum	0.2	0.16
Polygonum sagittatum	0.8	0.54
Ptilimnium capillaceum	2.0	1.35
Sagittaria latifolia	9.3	4.9
Schoenoplectus fluviatilis	8.5	5.7
Schoenoplectus tabernaemontani	3.4	1.41
Sium suave	0.5	0.38
Sparganium eurycarpum	1.7	1.19
Sparganium species	1.9	0.81
Symphyotrichum puniceum	7.7	4.52
Typha species	0.4	0.21
Unidentified species	3.1	1.36
Unidentified species 2	2.9	1.45
Zizania aquatica	0.1	0.05

The mean total percent cover for each Patuxent experimental plot in July of 2008 was about 96%. There was as little 29% and as much as 168% of a plot covered (Table 3.6).

Table 3.6: Vegetation parameters at Patuxent experimental plots, July 2008

Parameter	Mean	SE	Minimum	Maximum
Total # species/2.5m^2 plot	15.2	0.78	11	18
Total % Cover/2.5m^2 plot	95.7	14.45	28.5	167.5

IV. DISCUSSION

NANTICOKE RIVER OBSERVATIONAL STUDY

Surface Elevation and Accretion

The ability of coastal marshes to keep pace with rising sea level is dependent on their ability to maintain their surface elevation relative to sea level. Marsh surface elevation is controlled by many factors. Included in these factors are sediment deposition and export, organic matter accumulation, deposition, decomposition and export, deep processes such as geologic movements, and shallow processes including the seasonal shrink-swell of organic soils, erosion, and compaction (Cahoon 1999). The Chesapeake Bay has been experiencing rising sea levels, and in some cases such as Blackwater National Wildlife Refuge, the marshes are not keeping pace with sea level rise (Stevenson et al. 1985, Kearney et al. 1988). Marshes unable to maintain positive surface elevation above sea level are submerged or otherwise fragmented, converting to open water and tidal flats.

Climate

Climate has an influencing role on marsh elevation and accretion. Droughts decrease the amount of freshwater input which may expose the marsh to higher salinities and also to the effects of surface drying. Surface drying of the marsh can decrease elevation measurements by both increasing oxidation and thus decomposition rates and by causing a shrinkage in the organic soil layers.

Data from the National Oceanic and Atmospheric Administration (NOAA) indicate previous to study period, the Nanticoke River received normal amounts of precipitation in 2005 and above normal amounts of precipitation in 2006. During the period of study, the Nanticoke River received less than normal amounts of precipitation in 2007, between 889-1016 cm of precipitation, and normal amounts of precipitation in 2008, between 1016-1270 cm of precipitation. The beginning of 2009 was dryer than normal in January, February and March; however, April received above normal amounts of precipitation (NWS 2009).

In addition to precipitation trends, sites may have exhibited the identified short term trends because the influence of sea level during the course of the study. Although the overall sea level trend in Chesapeake Bay is increasing on average 3.48 cm/ year, the years of 2007-2009, years that elevation and accretion were measured, experienced a leveling off of sea level rise, and relative to 2006, a drop in sea level (NOAA 2009). A drop in sea level may increase marsh drying and associated degradation.

Elevation

The data suggest that oligohaline [salinity 0.5-5ppt (Cowardin et al. 1979)] (Sites 3,4) marshes are at the greatest risk of loss, followed by tidal fresh marshes [salinity <0.5ppt (Cowardin et al. 1979)] (Site 5) and lastly, the most stable of the Nanticoke River marshes appear to be the mesohaline [salinity 5-18ppt (Cowardin et al. 1979)] (approaching brackish) (Sites 1,2) marshes. There are many possible factors that may contribute to this trend. One possible factor is the depth of soil from the surface of the marsh to the underlying substrate. Site 1 had the shallowest soil (the least number of rods driven to point of refusal) and the highest organic matter content. A potential reason that it had positive accretion is that the organic soil layers have less mass to compact or decompose. There is a barrier of sand or other underlying substrate that prevents the organic soils from compacting deeper than the few meters of their depth. Despite having higher percentages of soil organic matter, the same amount of compaction or decomposition would have less of an effect at Site 1 compared to Site 3 due to the shallow depth of firm underlying substrate. Site 3 has a greater depth of soil to compact and thus may exhibit greater rates of elevation decrease. Additionally, as mentioned previously, sea level dropped during the course of measurement which may have caused some marshes to dry out or dewater. Drying out can oxidize the soils increasing decomposition rate.

Another potential reason that rates of elevation differed is the quality of the soil organic matter. Not all soil organic matter has the same ratio of labile to refractory compounds. Some vegetation is higher in lignin, a material harder to decompose, and may break down less quickly compared to plants with high amounts of labile compounds. Perhaps the vegetation at some sites is of a different quality than at others. Another hypothesis that could be explored as a factor contributing to differences in elevation is whether the oligohaline marshes are being acted on by the intrusion of more brackish, saline water being pushed up the estuary because of sea level rise. Salt water intrusion can cause organic soil collapse, and thus elevation loss, by way of rapid soil organic matter decomposition or belowground biomass death (DeLaune et al. 1994).These marshes may potentially be seeing the effects of salt water intrusion including an increased rate of organic soil decomposition because of exposure to sulfate and subsequently sulfate reduction (Weston et al. 2006). As mentioned previously, the oligohaline marshes have a greater column of soil compared to the mesohaline marshes that may provide a greater volume of soil to be acted on by saltwater intrusion. The mesohaline/brackish marshes had been exposed to salt water previously and may have already been affected, or formed under those conditions, in addition to having vegetation already adapted to salt water. Their soils are also shallower and possibly less susceptible to compaction, having a firm under layer closer to the surface of the marsh. There is also less soil to be acted on by decomposition. Another effect of salt water intrusion may be the collapse of a living root network due to salinity and sulfide-related mortality (DeLaune et. al 1994). The addition of salt water not only adds sulfate, increasing the rate of decomposition and producing vegetation-toxic sulfides, but also causes vegetation stress and death. Vegetation disturbance leads to pond formation, increased water levels, decreased accretion rates and channel network expansion which causes considerable marsh loss (Kirwan et al. 2008, Van der Wal and Pye 2004). Mesohaline/brackish marshes have significantly higher rates of elevation increase compared to the elevation loss of oligohaline marshes. It is possible that this may be because of highly organic soils in oligohaline marshes that are deeper compared to other marshes in the Nanticoke estuary and the effect of salt water intrusion and sulfate reduction.

There were no significant differences in rate of elevation change between five sites along the Nanticoke River; however, four are losing elevation despite rates of positive accretion. Site 3, an oligohaline site, is losing the greatest amount of elevation, decreasing 19 ± 7.5mm/year over the last 2 years despite a positive accretion rate of 16 ±5.7 mm. Site 1 had the only positive elevation rate, although, it is interesting to note that Site 2 decreased in elevation less than the 3 sites upriver, and it is possible that Site 2 would have had positive elevation had it not been burned by the landowners for muskrat and duck hunting. 2/3 replicate SET sites at Site 2 had been burned at least once during the course of this study.

As discussed, Site 1 may be exhibiting the only positive rate of elevation change due to the shallow depth to the underlying substrate. Another potential explanation for the greater stability of Site 1 and 2, mesohaline marshes, in the face of rising sea level may be their *Spartina cynosuroides*-dominated natural levees. *Spartina alterniflora* protects marsh shorelines from erosion and sea level rise by strengthening their soils with interlocking root systems (DeLaune 1994, Hartig 2002). It is possible that *Spartina cynosuroides*, which forms edges along the levees of Sites 1 and 2, may act in a similar way based on both species having rhizomatous growth forms (USDA Plants Database). *Spartina alterniflora* not only protects soils from erosion, but it also diminishes high tides resulting from storms and increases sediment deposition (Wan et al. 2009). As *Spartina alterniflora* is stressed and dies because of increased waterlogging it removes the structural support of its root system, allowing for increased erosion and vulnerability of marsh edges. Sites 2A and 2C were burned, 2A once in the winter of 2007 and 2C twice over the winters of 2007 and 2008, removing all of the above ground biomass but leaving the underground biomass intact. Site 2C had the lowest rate of accretion of the the 3 replicate SETs at Site 2. This indicates that the removal of aboveground *Spartina* vegetation may decrease the rate of accretion. Had Site 2 not been burned, the *S. cynosuroides*-dominated marshes would possibly have been protected from erosion due to higher sea levels and the ability of vegetation to decrease inundation velocities enough for sediment fallout. Surface sediments may have been eroded more because of the loss of vegetation. Site 2B, never having been burned, had the highest rate of accretion of the three replicates at Site 2. Site 1 maintained an edge of *Spartina cynosuroides* that fringed the levees along Site 1A and 1B. Site 1B had the highest rate of accretion at Site 1. Also, Site 3 may have a different quality of soil organic matter (different C:N ratios) since the vegetation communities are different between Site 3 and Site 2.

Another aspect that may lend stability to Sites 1 and 2 is the vegetation-engineered microtopography that creates oxidized mounds and reducing depressions. Stribling et al. (2007) found that vegetation in brackish and mesohaline marshes engineers the marsh surface creating hummocks and depressions to adapt to high salinity and sulfide levels. This adaptation enables vegetation to maximize growth under extreme and variable conditions, and also creates marsh bank-like sediments, which are more stable, on the tops of the hummocks. Site 2 in particular exhibited distinct hummock-depression microtopography. *Iva frutescens*, or high tide bush, has engineered Site 2 to have large hummocks and deep depressions. This would allow for higher accretion rates and greater plant growth compared to sites that do not have hummock-depression microtopograhy. Additionally *S. patens* creates smaller hummock-depression microtopography maximinzing growth and accretion rates under high salinity conditions (Stribling et al. 2007). Sites 1 and 2, dominated by *S. patens* and *S. cynosuroides* and *I. frutescens* respectively, have greater stability and Site 1 has positive elevation rates compared to oligohaline and freshwater marshes.The rate of overall elevation increase present in mesohaline/brackish marshes suggests that they are at a smaller risk of loss to sea level rise and may be more stable compared to oligohaline and tidal freshwater marshes.

Another aspect that may be contributing to elevation loss at these marsh sites is increased waterlogging. Though initial elevation decrease may be attributed to other factors such as increased salinity due to sea level rise, it may be exacerbated by relative sea level rise: water levels relatively higher because of sinking surface elevation. Increased waterlogging of the soils may promote compaction, thus exposing the soils to even more salt water intrusion and lowering vegetation growth rates (McKee and Mendelssohn 1989).

Elevation dynamics are long term processes that may not be accurately reflected in short term data. Further monitoring of the surface elevation tables would lend greater confidence to the elevation rate estimates

Accretion

The rates of accretion were variable and did not follow a salinity gradient trend; additionally, accretion rates were not significantly different between sites.R^2 values obtained from regression were closer to 1.0 for accretion rates compared to elevation measurements. There are three possible reasons proposed for this. The first is due to the greater variability of elevation measurements. Secondly, there is a greater spatial scale for elevation measurements. Finally, elevation measurements may have lower R^2 values because the regression line is taking into account points that both increase and decrease; comparatively, accretion rates in this study only increased. Accretion rates were not significantly different and Site 5, a tidal freshwater site, had the greatest observed amount of accretion. Accretion is influenced by many factors including the processes that control sedimentation. Sediment brought by high tides is an important factor in accretion. Historically, marshes have kept pace with rising sea levels due in part to the contribution of inorganic sedimentary accretion (Neubauer 2002). Inorganic sediment deposition is controlled by depth of inundation, vegetation density (dense vegetation decreases flooding velocities allowing the deposition of suspended sediments), tidal currents and sediment load, and rates of particle settling (Fitzgerald et al. 2008). Tidal freshwater marshes may be subject to differing levels of factors controlling accretion such as sediment load, depth of inundation and tidal currents. Other studies have shown accretion rates to be highest in tidal freshwater marshes (Craft 2007). One contributing factor to higher accretion rates in tidal freshwater marshes may be the estuarine turbidity maximum (ETM). Although the Nanticoke River may be a completely mixed estuary, it may experience some effects of an ETM and salt front as suggested by other studies (North and Houde 2001). As tidal currents push a wedge of salt water further upstream, the freshwater inputs of the river flow over it creating an area of turbidity where riverbed sediments are re-suspended. Additionally, this zone causes flocculation of suspended sediments. The ETM zone causes higher rates of sedimentation and thus accretion in tidal freshwater marshes (Liu et al. 2009). Proximity to the freshwater input of the Nanticoke River may also affect the amount of sediment received by tidal freshwater marshes. The soils of Sites 5 were less organic compared to other sites and exhibited some of the highest accretion rates. This may be because being the farthest upstream site, many sediments carried by the river from the upland may be deposited in the marshes surrounding Site 5 and when the river flows into the estuary near Site 1, many sediments may have already been deposited. Additionally, Sites 1,2, and 3 are adjacent to tidal creeks. Sites 4 and 5 are adjacent to the river. One possible explanation is that more sediments are deposited in marshes bordering the river than would be carried through tidal creeks and deposited in interior marshes.

Accretion and elevation are long term processes that require multiple years of study to identify an accurate trend. Two years of data provides an inadequate picture and significant differences may not be captured in such a short time frame. Despite the lack of statistical difference between the Nanticoke sites, It is possible that over time additional monitoring will reflect significant differences in accretion rate between the sites. Following the identified trend of tidal freshwater marshes having the highest accretion rates, the higher level of accretion at Site 5 may become significantly different from the sites further dowstream. To determine what factors create the variability of accretion rates, future study should include vegetation stem density measurements, water level monitoring, and measurements of suspended sediment load. Site 5 may have higher vegetation density that allows it to capture and settle greater amounts of sediments and suspended organic matter; however, being tidal fresh, the dominant decomposition pathway is most likely methanogenesis, a process that breaks down organic matter slower than sulfate reduction (Capone and Kiene 1988). If the oligohaline sites are being exposed to sulfate, and there is a decomposition process switchover from methanogenesis to sulfate reduction at those sites, then it would be expected that not only would they have a lower rate of accretion compared to tidal freshwater marshes not exposed to salt water intrusion, but they would also exhibit a greater loss of elevation compared to mesohaline/brackish marshes because they have deeper layers of organic matter-rich soils to be broken down through sulfate reduction. Additionally, oligohaline sites may be receiving less deposited inorganic sediments, evidenced by the higher organic matter content compared with the tidal freshwater marshes, and so may have less accretion, and may be more vulnerable to sulfate reduction because of their higher organic matter content compared to tidal freshwater marshes. The oligohaline sites are also in interior marshes in tidal creeks and so may receive less deposited organic material and sediments compared to tidal freshwater marshes that border the main Nanticoke River channel. The data do not reflect significant differences in accretion; however, based on a non-significant observational trend, with further data collection, it is possible that the accretion rate differences will become significantly different as sea level increases.

The lowest observed rates of accretion at Site 4. It is dominated by similar soil and vegetation as Site 5, which have the highest accretion rates, therefore the low accretion rates are most likely due to other sources of variability. The salinity at Site 5 was recorded consistently to be 0.1ppt-0.3ppt each time it was measured; however, the salinity of Site 4 varied between 0.1 ppt and 3.2ppt. The higher salinity may inhibit plants of the same species from growing as large at Site 4 compared to at Site 5 (McKee and Mendelssohn 1989). Additionally, Site 4 has a public boat launch directly across the river from 4C, and near 4B and 4A on the same side as the boat launch. Increased boat activity may increase erosion of wetlands (Hartig 2002). Site 5 is further upstream and so may receive more suspended sediment load running off from upland sites as well.

Other factors may have influenced the Nanticoke River sites including erosion due to barge wakes, dredging the river channel to accommodate barges (Hartig 2002), biological activities such as muskrat burrows (Ford 1998), and poor land management practices such as marsh burning.

PATUXENT EXPERIMENTAL STUDY

Changing salinity and hydroperiod because of relative sea level rise will alter vegetation communities in tidal freshwater marsh systems. It is not yet clear whether sea level rise will affect all tidal freshwater marsh communities in a uniform way; however, salt and brackish marshes exposed to increasing salinity and water level have exhibited a shoreward movement of monoculture bands typical of these marshes. In a New England salt marsh study, Warren and Niering (1993) found that bands of *Spartina cynosuroides*, typically a marsh edge monoculture, moved inland replacing the band of *Spartina patens*, which in turn replaced the further inland band of *Juncus gerardi.*

In addition to causing shoreward movement of salt-tolerant species, increased salinity causes vegetation stress and death, lower productivity, and higher rates of organic matter decomposition (McKee and Mendelssohn 1989).

Salinity treatments decreased the number of seedling species in Patuxent River experimental plots. Fewer species of wetland macrophyte are adapted to live in brackish or salt water conditions compared to tidal freshwater systems. Salinity treatments may have created an environment inhospitable for seed germination or seedling growth of species with low salt tolerances. With rising sea levels, greater areas of oligohaline and tidal freshwater marshes will be exposed to increasing salinity. This increased salinity may cause a shift in species composition from biodiverse tidal freshwater marsh communities, to less diverse communities of macrophytes with higher salt tolerances. Tidal freshwater marshes have higher biodiversity and greater numbers of species compared to brakish and salt marsh communities (Gosselink 1984, Odum 1988). Not only will there be increased vegetation stress, decreasing primary production, but salt water intrusion may cause vegetation death and inhibit the germination and establishment of some vegetation species, possibly decreasing the overall vegetation cover (Total % cover) and creating communities with greater numbers of monocultures and decreased biodiversity

Additionally, over time, salinity treatments may cause a decomposition shift from methanogenesis to sulfate reduction in the Patuxent experimental marsh plots. This switch from methanogenesis to sulfate reduction may cause rapid subsidence of the Patuxent marsh soils and subsequently a rapid drop in elevation.

PROBLEMS AND SUGGESTIONS FOR FUTURE STUDY

Elevation and accretion measurements are long term processes that require long term study to determine relevant trends. Further monitoring of SETs is necessary to understand the elevation trends along the Nanticoke River. Two years of data are insufficient to base any conclusions regarding long term elevation trends on. Two years of data reflect short term trends only.

As previously mentioned, two of theNanticoke River observational SET sites were burned by land owners during the study period. This may have affected both accretion and elevation measurements. Since the autocthonous organic carbon was incinerated rather than decomposing on the surface, it is possible that the accretion rates were lower than they would have been had the site not been burned. Additionally, without burning, elevation measurements may have increased rather than decreasing. This is because of the higher accretion rates and the impact of the dominant vegetation, *S. cynosuroides*, on sediment deposition, degree of inundation and erosion.

Additionally, further study of the Nanticoke observational plots would lend additional information that may indicate the ecological reasons behind the observed patterns. For example, examining the dominant decomposition processes over time, including during droughts when salt wedges are pushed further upstream to determine whether at soil depths, there is peat collapse or death of the living root network influencing surface elevation. This would be useful in testing the hypothesis that oligohaline marshes are seeing the greatest loss of elevation due to sulfate reduction impacts resulting from exposure to more brackish and salt water.

Additionally, determining the direct impact of salt water intrusion by monitoring the elevation and sulfide levels at the Patuxent experimental plots will help determine whether there is a rapid subsidence in surface level after sulfate reduction occurs in the methanogenesis-dominated marshes.

The Patuxent River experiment had problems that prevented execution of enough treatments for meaningful elevation change data. Had treatments been applied as planned, every two weeks 378.5 liters (100 gal) of treatment water irrigated the surface of the plots, vegetation data would most likely have shown more significant differences between the salt and freshwater plots. Additionally, upon measuring surface elevation, a significant drop in elevation may have been seen due to the increased decomposition rate of the highly organic soils.

However, constructing the irrigation system took much longer than planned and was frought with many more complications and problems. Pump operation was variable and ineffective at times, preventing treatment application. Additionally, biofilms clogged the valves and even larvae that managed to get inside the tanks clogged the valves from dispersing treatment. Also, the permeable soaker hoses were sealed by algae and other biofilms.

In the future, a new method of treatment dispersal may need to be developed to be more consistent. Perhaps using a pump operated sprinkler system to disperse treatment quickly and evenly may be more successful than the current method.

One issue was the amount of time it took initially to fill the 378.5 liter tanks. Treatments were begun with a smaller gasoline powered Honda pump, but because of the friction of using 90 m of garden hose, the pump could hardly push the water through the 1.9 cm inner diameter hose. Additionally, maneuvering the hoses through the dense vegetation took as long as filling the tanks. To make the process more efficient, a new, more powerful pump and new, wider hoses were utilized. The hoses were staked in place so that they would not have to be moved during filling and hose splitters were installed so that all sites could fill simultaneously. This sped the process up from 55 minutes/tank+20 minutes for hose maneuvering +1 hour to wind 92 m of muddy hose up to only 10-15 minutes/tank to fill.

Another reason why the vegetation data reflected few treatment differences was because treatments were begun at salinity levels that were nearly imperceptible (1ppt) and treatment effects were not measured until 2 weeks after the weak treatments had been applied. The initial concern was that if too high a salinity were used, vegetation would be killed and then instead of seeing a drop in elevation because of sulfate reduction, there would be a drop only because of the collapse of the living root network and aboveground biomass. However, after applying 10ppt salinity, the vegetation persisted, indicating that it is hardier than was expected or that dilution was rapid.

To remedy the biofilm clogging, needle valves were removed and replaced with tees that have wider inner diameters and should clog less easily. Additionally, despite the fact that black tubing was purchased to reduce algae growth inside the tubes, the soaker hoses still clogged. To allow for treatment flow, an awl was used to stab holes every 2.54 cm along the length of the hose.

The Nanticoke River observational study and the Patuxent River experimental study are both important to understanding how sea level rise affects tidal freshwater marshes. More data observing a greater number of factors including sedimentation, vegetation density, decomposition type and rates at the Nanticoke River observational plots and the continuation of the Patuxent River experiment with subsequent elevation monitoring would illuminate the current observed trends in elevation, vegetation, and accretion data, and may give a better idea as to how and why marshes of the US Atlantic coast are being lost.

V. CONCLUSION

To date, few studies have examined the effects of sea level rise on tidal freshwater marshes, marshes that may be particularly vulnerable to the effects of increasing salinity and water level, and the addition of sulfate. This study focused on observing the current state of tidal freshwater wetlands, in particular, the accretion and elevation dynamics, and on simulating saltwater intrusion to determine its effects on these marshes. It was hypothesized that tidal freshwater marshes would experience the greatest level of degradation relative to oligohaline and mesohaline marshes due to sea level rise because of their highly organic soils, their present dominant decomposition pathway, and their freshwater vegetation types. The data suggest that at this point oligohaline marshes are suffering the greatest losses in elevation, a factor that could escalate other mechanisms of marsh loss such as salt stress, increased decomposition, and increased waterlogging. However, on the Nanticoke River, tidal freshwater marshes have not yet been exposed to increased salinity as observed in the salinity data from Site 5, and potential damage is yet to be seen. Based on the effect of saline treatments at the Patuxent River, greater losses of biodiversity and elevation will be seen in tidal freshwater marshes in the future than are now seen at oligohaline marshes. As sea level rises and salt water is pushed further inland, freshwater marshes will exhibit greater sensitivity and may experience significant losses of elevation and subsequent flooding. One mechanism of marsh loss that has been examined little is the increased rate of decomposition as methanogenesis switches to sulfate reduction with the introduction of sulfate present in sea water. Perhaps the degradation seen now at oligohaline marshes is a results of exposure to sulfate which will have a more profound effect when it contacts the highly organic soils of tidal freshwater marshes.

The view that insufficient accretion rates are the primary cause of marsh loss may not be incorporating the entire picture. Other studies have concluded that if accretion rates surpass rates of relative sea level rise, then those marshes are stable and will keep pace with rising sea levels (Neubauer 2008); however, this study indicates that despite short term rates of accretion greater than relative sea level rise, the overall elevation of Nanticoke River marshes is decreasing indicating that they will not keep pace with sea level rise. Simply examining the accretion rates and the rate of sea level rise does not provide for a host of other mechanisms of marsh loss that may be at least as important as insufficient accretion rates. For example, Hartig et al. (2002) identifies an increasing channel network, boat traffic and dredging acting synergistically as mechanisms of marsh loss rather than vertical submergence of interior marsh, the widely held view(DeLaune et al. 1983, 1987, Stevenson et al. 1986, Titus 1988).

A multi-disciplinary management approach incorporating multiple anthropogenic and natural-process potential threats to tidal freshwater marshes may increase the effectiveness of current practices. However, if mechanisms of marsh loss are not explored exhaustively, coastal marshes in the Chesapeake Bay area may experience widespread loss and degradation similar to what has been seen in coastal Louisiana.

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