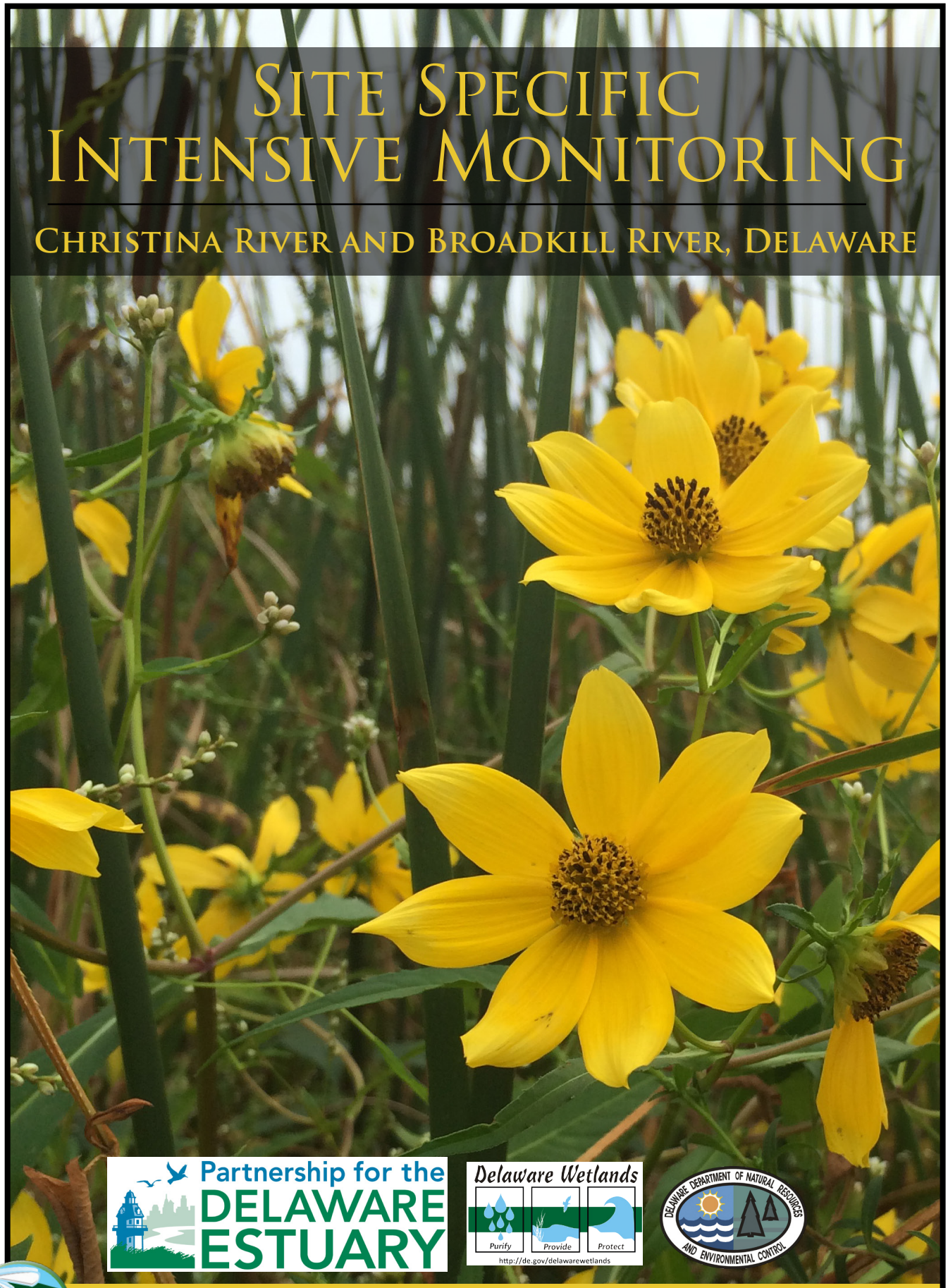
Mid Atlantic Coastal Wetland Assessment

Site Specific Intensive Monitoring

Christina River and Broadkill River, Delaware



Partnership for the Delaware Estuary

Delaware Wetlands
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Delaware Department of Natural Resources and Environmental Control

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Partnership for the Delaware Estuary
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Cover photograph of Showy Bur-marigold (*Bidens laevis*) along the Christina River by LeeAnn Haaf.

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Introduction

Coastal wetlands are a hallmark feature of Delaware's Bayshore, making up about 23% of all wetland types in the state (Tiner et al. 2011). They provide a variety of services to coastal communities such as flood abatement, wave attenuation, nutrient sequestration, and water quality enhancement. Because of the many services these ecosystem provide, resilience of coastal wetlands is an important part of sustaining and protecting coastal communities from threats associated with the changing climate (Arkema *et al.* 2013), such as sea level rise and prolonged weather patterns that increase the probabilities of extreme storm events (Francis and Vavrus 2012), as well as various types of anthropogenic stress. Relationships between sediment loads and plant community robustness create a dynamic system that naturally sustains coastal wetland resilience.

Impaired coastal wetlands, however, have a limited capacity to perform important ecosystem services for adjacent residential communities. For instance, extremely high levels of nutrient enrichment, however, induce a negative feedback that alters plant productivity and reduces marsh resilience (Deegan *et al*. 2012). This is just one example of how the culmination of resilience reducing anthropogenic activities has led to broad scale declines in marsh acreage, limiting the services coastal wetlands can provide. Over the past 40 years human populations in the Mid Atlantic have drastically increased (between 20-100%) and sediment sources important to coastal wetland sustainability have decreased (Weston 2014). Data and observations of marsh condition in Delaware as well as across the Delaware Estuary suggest that many marshes in these areas suffer greatly from various forms of human-induced stress (Kreeger and Padeletti 2013; Jennette *et al.* 2014).

With more human disturbance and reductions in sediment supplies, the processes which make coastal wetlands resilient to climate change and sea level rise may diminish, which generally results in mudflat or open water conversion. From 1992-2007 much of the loss of estuarine habitats in Delaware were attributed to open water conversion (83%; Tiner et al. 2011). Because healthy coastal wetlands are an integral part of the cumulative health of the Delaware Estuary, the restoration of areas in poor condition is a regional priority. Successful restoration, management, and health of coastal wetlands is supported by an improved understanding of how coastal wetlands respond to stressors and how these areas are faring over time.

Mid Atlantic Coastal Wetland Assessment

Due to their importance in the region, in 2006 coastal wetland condition research became one of the Partnership for the Delaware Estuary's (PDE; a National Estuary Program) top priorities. And in 2008, a multi-level Mid Atlantic Coastal Wetland Assessment (MACWA) was established to support a more comprehensive means of assessing coastal wetland condition across the Mid Atlantic region. Since then, PDE and partners, especially Delaware Natural Resources and Environmental Control (DNREC)'s Wetland Assessment Group, have worked to implement MACWA as a coastal wetland strategy, which is continuously updated and strengthened.

MACWA is a 4-tier monitoring and assessment program envisioned to provide rigorous, comparable data across all tidal wetlands of the Mid Atlantic, especially those in the Delaware Estuary within Delaware, New Jersey, and Pennsylvania, as well as Barnegat Bay in New Jersey. It has become a platform through which research is conducted and data is mined for various purposes. The strategy of MACWA follows EPA national guidance (U.S. EPA 2001) (Figure 1):

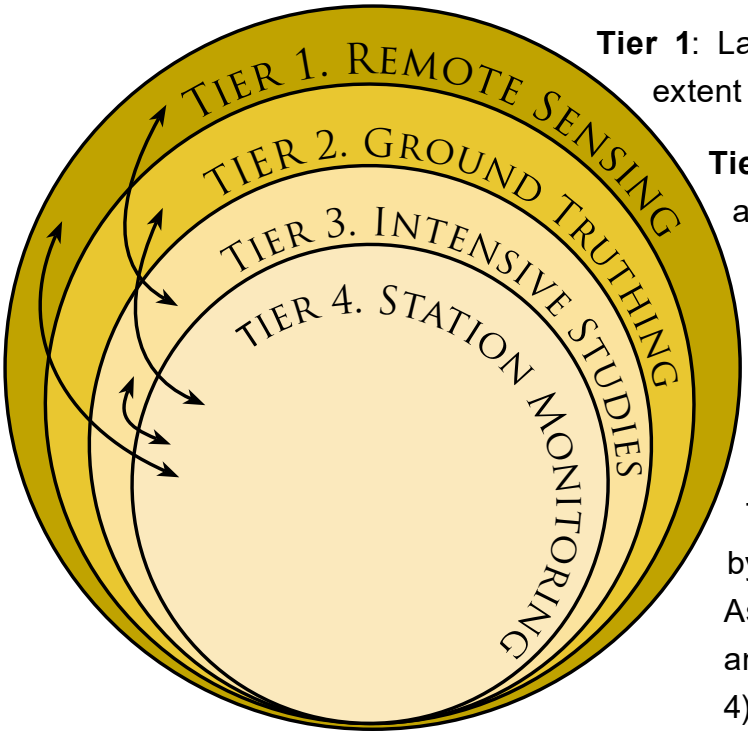

Figure 1. The four tiers of the Mid Atlantic Coastal Wetland Assessment.

Tier 1: Landscape census surveys (remote sensing) of extent and loss

Tier 2: Probabilistic sampling on-the-ground across the study region to assess condition

Tier 3: Intensive studies to examine relationships among condition, function, and stressor impacts

Tier 4: Intensive monitoring function at a networked array of fixed stations

The objectives of Tier 2 and 4 are carried out by two subprograms: Mid Atlantic Tidal Rapid Assessment Method (MidTRAM or RAM; Tier 2) and Site Specific Intensive Monitoring (SSIM, Tier 4). SSIM datasets can be used as a data mine for other studies, such as those which attempt to estimate ecosystem services. Ecosystem service studies, or other studies that seek to answer specific questions which would improve our understanding of marsh ecology and restoration fall into Tier 3. Furthermore, each tier is designed to substantiate other tiers. For example, ground truthing assessments (Tier 2) are used to verify projections of marsh loss as derived from satellite imagery or remote sensing studies in Tier 1. Previous reports relating to MACWA are available through the Partnership for the Delaware Estuary's website (www.delawareestuary.org/Wetlands).

The goal of this report is to summarize data and relevant findings from Site Specific Intensive Monitoring carried out in the Christina River (6 years of effort) and Broadkill Rivers (3 years of effort) within the state of Delaware.

Methodology

Site Specific Intensive Monitoring

Long term monitoring (LTM) is an essential part of understanding coastal marsh condition over time, as well as the stressor-response relationships that underpin condition. A special topic of interest in MACWA's LTM program, Site Specific Monitoring (SSIM), is to understand the factors which govern coastal marsh resilience over time at precise locations. This allows researchers to tease apart relationships that pertain to the temporal responses of these habitats to stressors. Although these

systems are complex, a substantial body of literature (Table 1) exists regarding dynamics that can be important for marsh persistence. Several metrics, codified by the scientific community, are collected as part of SSIM so that these particular responses can be monitored. It is important to note that these data, and the enhanced understanding of marsh responses to stressors, is an essential part of designing, monitoring, and improving the outcomes of successful restoration projects. Details on metrics and data collection methodologies is furnished through the SSIM Quality Assurance Protection Plan (available at www.delawareestuary.org/node/199).

To date, PDE and partners have installed 11 SSIM stations: 7 in the Delaware Estuary and 4 in the Barnegat Bay Estuary (Figure 2). Additional stations are being planned in New Jersey and New York. Since SSIM stations were all installed and monitored consistently, the network of stations

Table 1. Metrics collected as part of the Site Specific Intensive Monitoring program.

	Metric	Methodology	Citation
Surface Dynamics	Surface Elevation Change	Deep rod surface elevation tables	Lynch et al. (2015)
	Surface Accretion	Feldspar Marker Horizons	Lynch et al. (2015)
	Surface Elevation	Real Time Kinematic (RTK) GPS transect (vegetation-based) or grid (platform/feature-based) surveys	USGS (2012); Raposa et al. (2016)
Vegetation Dynamics	Vegetation Height	Plot specific height measurements	Mendelsshon and Seneca (1979)
	Plant Community Structure	Species richness, estimated cover	Donnelly and Bertness (2001)
	Vegetative Productivity	Above and below ground biomass (hand sorting)	Cahoon et al. (2002); Morris et al. (2002); Cahoon (2015);
Soil Quality	Soil Nutrients	Nitrogen, Phosphorus (laboratory analyses, by depth)	Quirk et al. (2015a/b); Raper et al. (2016)
	Soil Carbon	Carbon, bulk density (laboratory analyses, by depth)	Quirk et al. (2015a/b); Raper et al. (2016)
Water Quality	Water Nutrients	NOx, NHx, SRP, Alkalinity (laboratory analyses); Turbidity	Nitogen: Deegan et al. (2012); Turbidity: Raposa et al. (2016)
	Water Quality	Temperature, Conductance (salinity), Dissolved Oxygen, Total Dissolved Solids, pH (*in situ* YSI readings)	Quirk et al. (2015a/b); Raper et al. (2016)
	Suspended Sediments	Total Suspended Solids (laboratory analysis)	Morris et al. (2002); Fagherazzi et al. (2012); Kirwan et al. (2015)

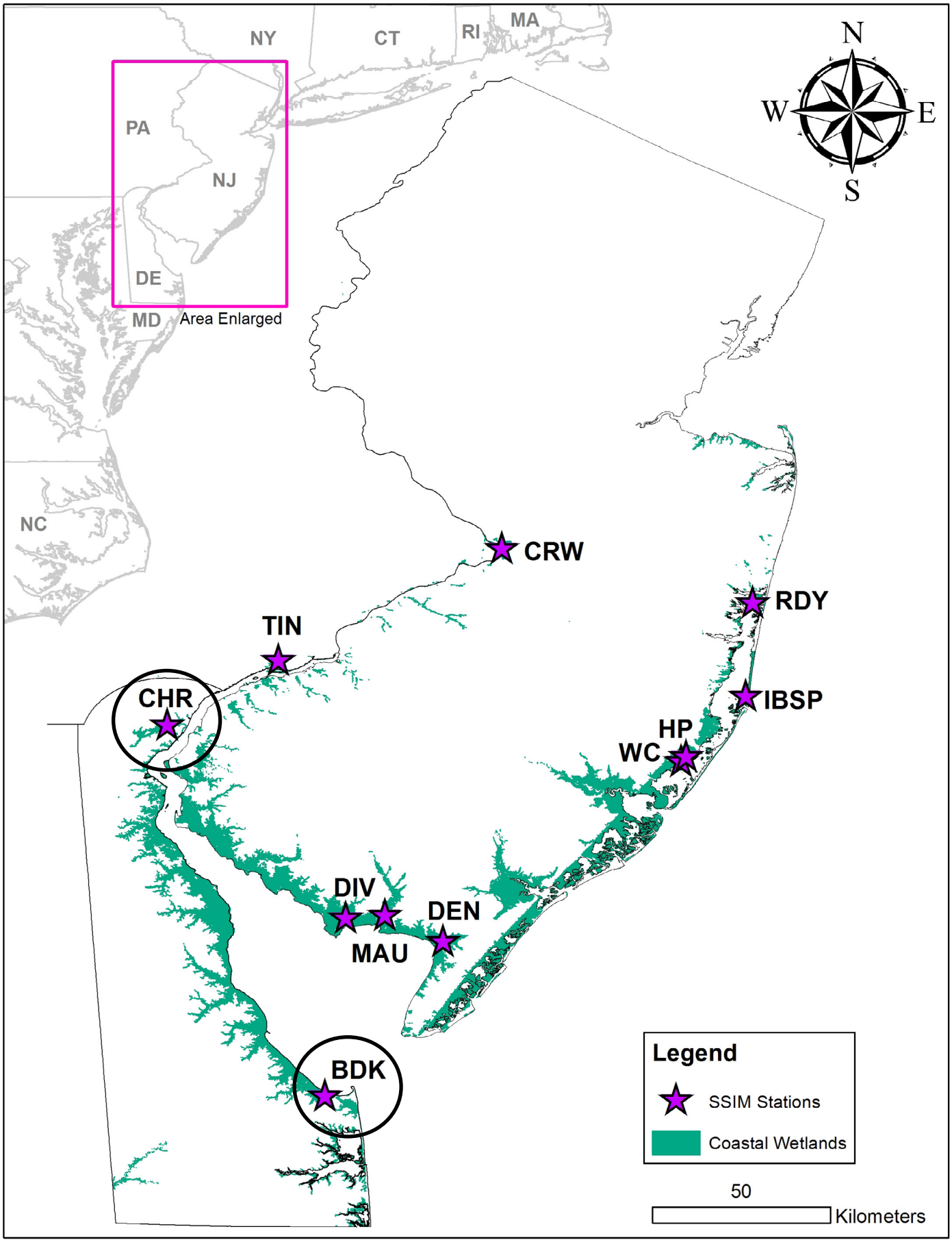

Figure 2. Site Specific Intensive Monitoring stations in the coastal wetlands (teal) of New Jersey, Delaware, and Pennsylvania. Delaware stations (circled in black) are the Christina River (CHR) and the Broadkill River (BDK).

across several geographical regions makes results of these efforts comparable, offering insight into spatial variability and the effects of different environmental parameters, such as tidal height, coastal storm landfall impacts, or the degree of urbanization.

Each SSIM station has 3 surface elevation tables (SET), each of which are coupled with 3 marker horizon plots (MH) to discern surface accretion; these two methods are used in conjunction to track shallow subsidence (*sensu* Lynch et al. 2015). Each unit of 1 SET with 3 MHs is referred to as a SET-MH. SET-MHs are read 2 to 3 times a year. Each SET-MH is accompanied by three 1 m^2 permanent vegetation plots, which are located in the proximity of the SET-MH in a representative plant community. Biomass and soil quality samples are exacted in the general vicinity of SETs 1 and 3, every 2-3 years. Additional vegetation plots (n=6) of 0.25 m^2 are randomly located along the main channel to gather data on the plant communities along creek edges. Metrics which involve surveying vegetation, including real time kinematic (RTK) GPS surveys, are conducted in July-August. Each station is monitored within 1-2 weeks of the original sampling date to facilitate seasonal sampling consistency. RTK platform grids, a new addition in the 2015 season (not yet performed in Delaware), which are more intensive than transects, might be completed at any time of year, once every 2-3 years within a similar season. Water quality data, both water collection and YSI measurements, are sampled at 5 established points along each main channel three times annually.

Monitoring Stations in Delaware

Christina River

The Christina River is the major riverine drainage in the northern part of Delaware. Its watershed area reaches across New Castle County, and drains portions of northern Maryland and southeastern Pennsylvania. The Christina River's confluence with the Delaware River is located in Wilmington, just upstream of the Delaware Memorial Bridge, which on average, marks the Delaware Estuary's salt line (where salinity is ~0.25 ppt; DRBC 2016). The tidal portion of the Christina River extends upstream approximately 15 kilometers from its confluence with the Delaware River. This tidal corridor is heavily urbanized and small pockets of tidal freshwater marsh (specifically oligohaline or ~0.5 ppt on average) exist along its meandering path. These marshes are dominated by herbaceous plants such as *Nuphar lutea, Typha angustifolia, Peltandra virginica, Impatiens capensis, Pontedaria cordata, Schoenoplectus fluvialitis,* and *Bidens* spp. (Figure 3).

Figure 3. Typical vegetation community at the Christina River SSIM station: *Peltandra virginica* (right foreground) and *Typha angustifolia* (top background).

The Christina SSIM station is located in the Russell Peterson Urban Wildlife Refuge. The area continues to be impacted by both current and legacy pollutants associated wtih the chemical industry,

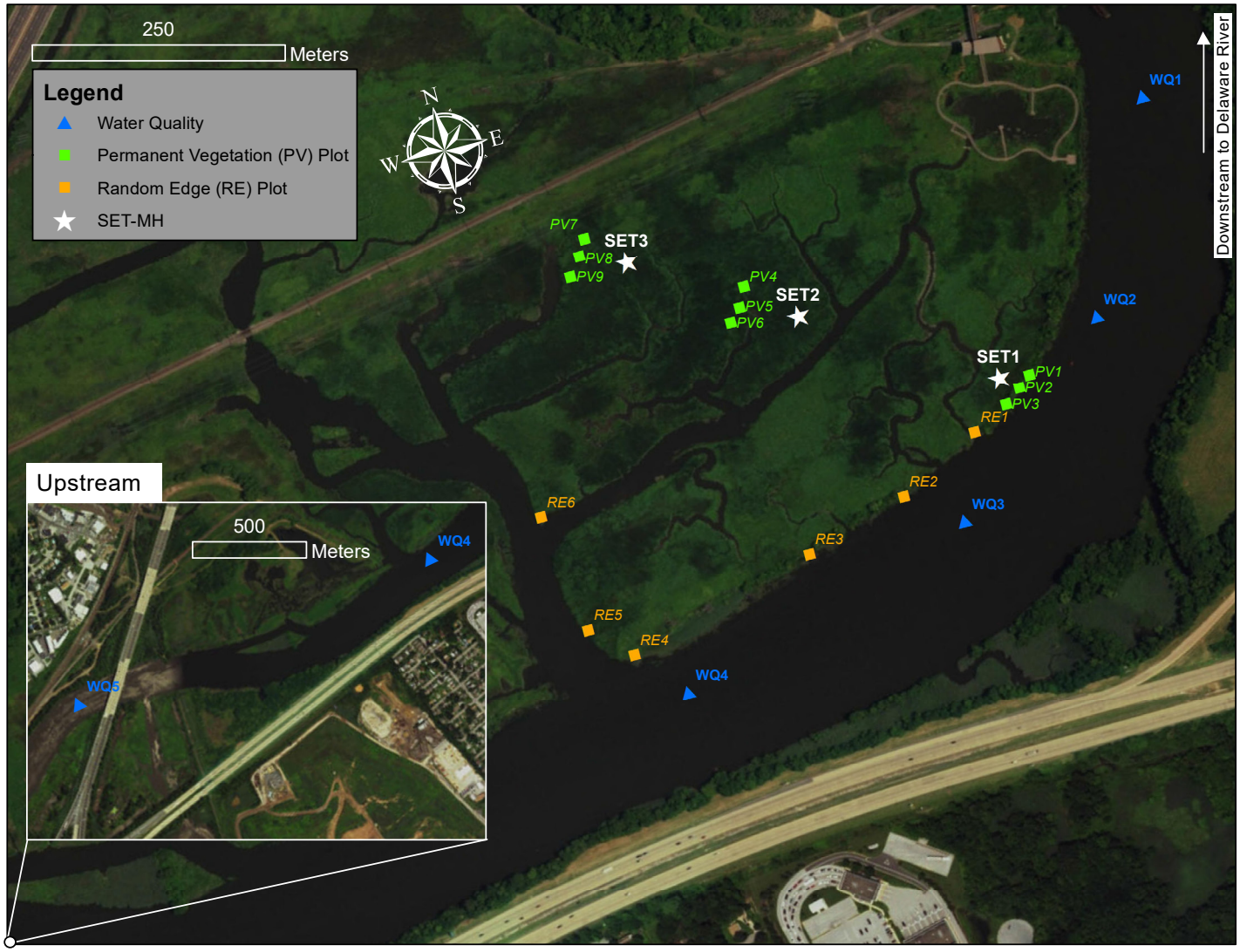

Figure 4. The Christina River SSIM station in Wilmington, New Castle County, Delaware. Inset shows water quality stations 4 and 5, upstream of the current map extent.

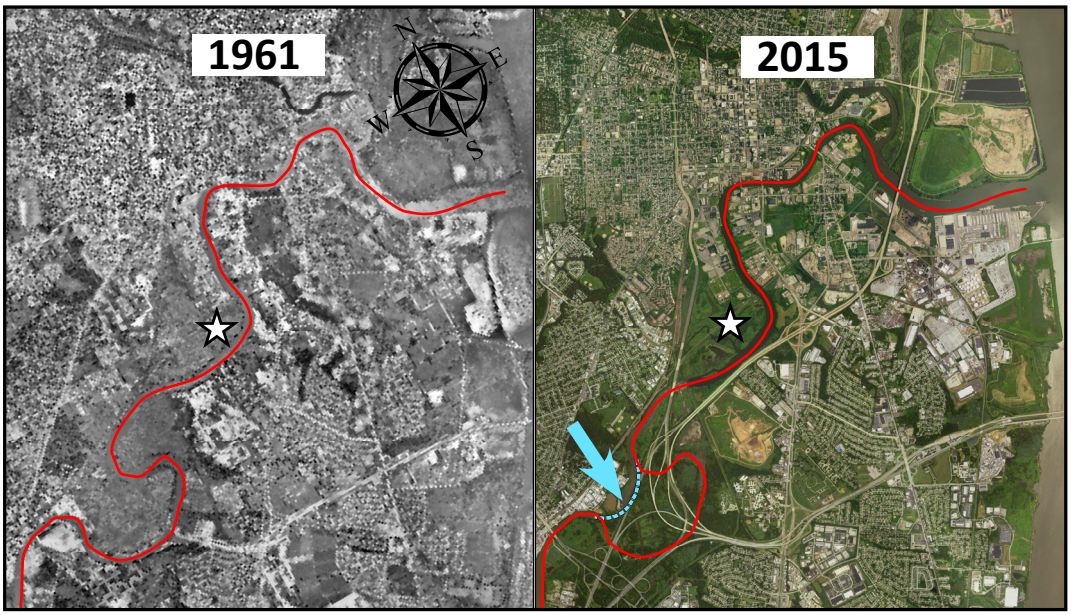

Figure 5. Diversion (dashed blue line, see blue arrow) of the Christina River's natural course (red) to accommodate highway intersections (I495, I295, and I95). The location of the SSIM station is noted with a white star.

and from fragmentation caused by the construction of highways in the 1960's. Highway construction included the diversion of the river's course to accommodate the convergence of the three interstate highways (I495, I295, and I95; Figure 5). The Christina River SSIM station was established in 2010, when it's surface elevation tables (SETs; N=3) were installed. The station's first SET first readings were completed March 15, 2011. As of 2016, six years of annual monitoring have been completed for this station.

Broadkill River

The Broadkill River, Canary Creek, and the Lewes Canal are the three most downstream channels that drain into the Delaware Bay within the state of Delaware. These three channels form one confluence, Roosevelt Inlet, which discharges into the Bay. The Broadkill SSIM station is located along Canary Creek. The expansive marsh area between the most downstream section of the Broadkill River and Canary Creek is part of the Great Marsh Preserve (Figure 6). Southeast of the site is the city of Lewes, Delaware, which is a small residential community impacted mostly by the summer influx of beach tourists. The surrounding landscape is generally agricultural, with some medium density housing. Like most salt marshes along the east coast, these areas were historically ditched for mosquito population control.

The Broadkill SET-MHs and permanent plots were installed in 2014 (Figure 7 and 8). There are three years (2014, 2015, 2016) of monitoring data for this station. Being so close to the Delaware Bay's confluence with the Atlantic Ocean introduces high levels of saline water to these marshes; salinities are typically ≥20 ppt. This is the most saline SSIM station in the Delaware Estuary. Dominant plants at the Broadkill SSIM station include *Spartina alterniflora, Spartina patens,* and *Distichlis spicata*.

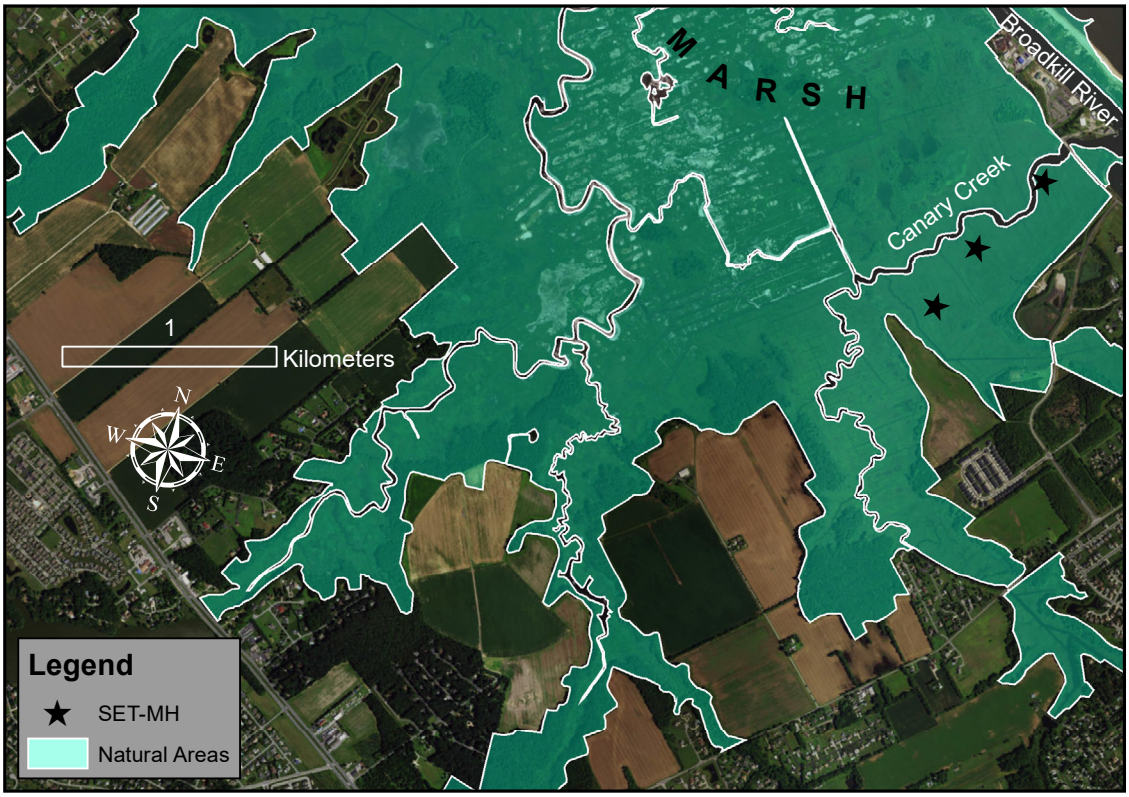

Figure 6. The Broadkill SSIM station, along Canary Creek, is part of the expansive salt marsh complex of the Great Marsh Preserve.

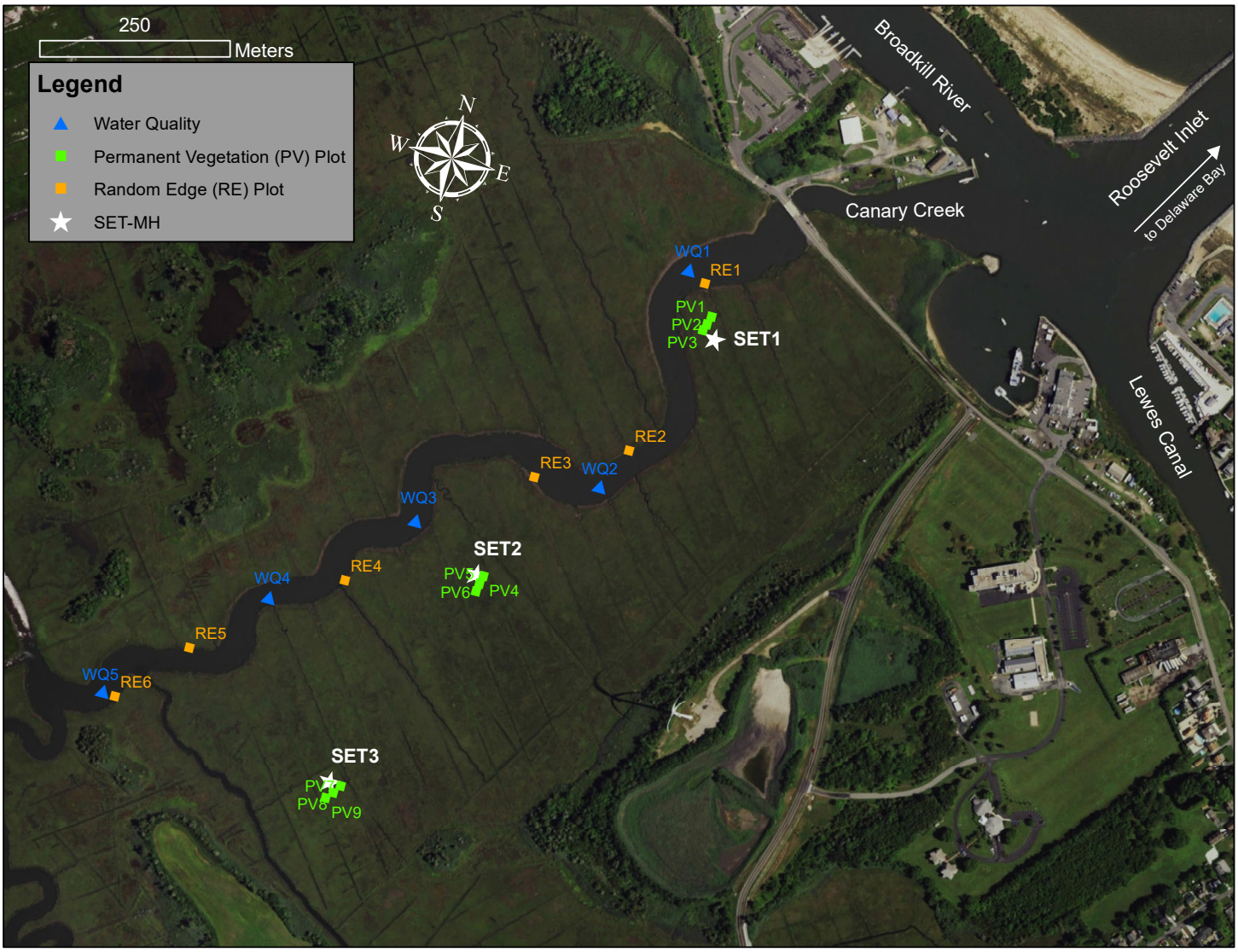

Figure 7. The Broadkill SSIM station in Lewes, Sussex County, Delaware.

Figure 8. Summer monitoring in 2016 at the Broadkill River SSIM station surrounded by *Spartina alterniflora*: measuring marker horizons (left) and collecting vegetation plot data (right).

Methodological Approaches*

Elevation Dynamics

Surface Elevation Tables and Marker Horizons

Surface elevation tables (SETs) and marker horizons (MHs) were read 2-3 times a year, in spring, summer and/or fall (Table 2). For both stations, SET data were analyzed by linear regression models using the cumulative change in pin heights. Cumulative changes in heights across the four arm positions of the SET were averaged for this analysis. Accretion was measured as the depth of accumulated material above a feldspar marker layer. These data were also analyzed per SET using linear regressions of the average of 3 marker horizon plots per SET. Variation was expressed as standard error of the pins for SETs and of the plots for accretion. Analyses follow standardized protocols developed by Lynch et al. (2015).

Platform Elevation through RTK GPS

In 2011, 2012, 2014, 2015, and 2016 three established transects were surveyed per SET at the Christina SSIM station using a real time kinematic (RTK) GPS, which measures elevation with a vertical accuracy of ~<6 cm. Similarly, in Broadkill, 3 established transects were surveyed using RTK GPS at each SET in 2014, 2015, and 2016. These data were imported into ArcMap (v 10.4) and rasters were built using the IDW (inverse distance weighted) interpolation tool (3D Analyst). Using a reference transect, profiles of surface elevations for each year were generated through ArcMap's Stack Profiler (3D Analyst). These profile data were then graphed by year in R Statical Computing Software (https://www.r-project.org/).

Vegetation Dynamics

Vegetation Plots

A total of eighteen permanent vegetation plots of 1m^2 were surveyed annually in early July at Christina and late August in Broadkill. Each permanent vegetation plot was assessed for 3 metrics: species cover, canopy obstruction (light intensity), and blade heights. Species cover and canopy obstruction were plot level and so were averaged among each triplicate, sets of three PVs grouped near each other (PVs 1, 2, 3; 4, 5, 6; and 7, 8, 9; or "near", "mid", and "far," respectively). Blade height data were collected by taking 25 random stems in each plot, which were averaged to derive mean blade height per plot. These were then averaged across sets of triplicates. Linear regression models were run in R; variation was expressed as standard error. Six random edge plots were also surveyed as part of vegetation monitoring. These data were assessed similarly, but linear models were not run as user-generated variation existed from year to year. Those data are located in Appendix I.

Vegetative Productivity

Vegetative productivity was examined through triplicate above and below ground biomass extracted near SETs 1 and 3. Sample locations are chosen in representative areas, where previous extraction sites are avoided. For Christina, above ground materials were collected in 1 m^2 plots; for Broadkill, 0.25 m^2 was used as plant variability is generally lower in saline systems. Values for Broadkill were

*For more information, please see the 2010 SSIM Umbrella QAPP.

Table 2. Schedule of completed and current data collection for the Christina and Broadkill SSIM stations. The abbreviations are as follows: 1x - taken once per year; 2x - twice per year; 3x - three times per year; P - in progress.

Metric	Christina								Broadkill			
	2010	2011	2012	2013	2014	2015	2016	2017	2014	2015	2016	2017
Surface Elevation Change	-	2x	2x	2x	3x	3x	3x	P	2x	3x	3x	P
Surface Accretion	-	2x	2x	2x	3x	3x	3x	P	2x	3x	3x	P
Surface Elevation (RTK)	-	1x	1x	-	1x	1x	1x	-	1x	1x	1x	-
Vegetation Height	-	1x	1x	1x	1x	1x	1x	P	1x	1x	1x	P
Plant Community Structure	-	1x	1x	1x	1x	1x	1x	P	1x	1x	1x	P
Vegetative Productivity	-	1x	-	1x	1x	1x	-	-	1x	1x	1x	-
Soil Nutrients	1x	1x	1x	1x	1x	1x	-	-	1x	1x	1x	-
Soil Carbon	-	1x	1x	1x	1x	1x	-	-	1x	1x	1x	-
Water Nutrients	-	3x	3x	3x	3x	3x	3x	P	-	3x	3x	P
Water Quality	-	3x	3x	3x	3x	3x	3x	P	2x	3x	3x	P
Suspended Sediments	-	3x	3x	3x	3x	3x	3x	P	-	3x	3x	P

extrapolated to 1 m^2 for analyses. Four metrics were collected for above ground material: plant species; live/dead material by species; stem height; and stem density. Below ground materials were collected in 6" PVC corers, 30 cm deep. Three metrics were collected via hand sorting of roots and rhizomes by two depth classes (0-15 and 15-30 cm): plant species; and live/dead material by species. Below ground materials from both stations were extrapolated to 1 m^2.

Biomass sampling is a destructive technique, so it cannot be collected at precisely the same location year after year. Due to the inherent spatial variation of plant communities and limited samples sizes, several years of data (5+) are necessary to produce meaningful analyses, but simple regression were calculated for available data. Average variance* among all years was calculated to give future comparisons of biomass at Christina and Broadkill. Values were calculated as the means of triplicate samples from SETs 1 and 3.

Soil Quality

Nutrients and Carbon

Triplicate soil cores (5 cm diameter x 30 cm depth) were collected at SETs 1 and 3 near biomass plots. Soil organic content, bulk density, and quality (% carbon, nitrogen, phosphorus and loss on ignition) were analyzed by 2 cm increments down the core (0-30 cm). Inorganic/organic matter deposition was assessed using percent loss on ignition (450°C, 8 hours). Total organic carbon and total nitrogen were measured using a CE Flash Elemental Analyzer following the guidelines in EPA 440.0 and manufacturer instructions. Samples were pre-treated with acid to remove inorganic carbon. Soil quality data were processed by the Academy of Natural Sciences of Drexel University (*sensu* Quirk et al. 2015). Linear regressions were not run on these data; future reports will perform more robust multivariate statistics investigating factors for nutrients, time, and depth. Data were summarized over time by depth at each sampling location (i.e. SET 1 or SET 3).

Water Quality

Five sampling points were established along the main channel at each station for spot water quality measurements using a handheld YSI Professional Plus. Surface water was collected on incoming tides. Due to the inherent complexity of water conditions and the limitation of these sampling techniques, linear regressions to investigate change over time were not run on these data. More data will be necessary to perform reliable statistics. Data were summarized by means for all dates and sample locations.

Water Condition

Water column temperature, salinity (ppt), dissolved oxygen (DO; % and mg/L), total dissolved solids, and pH were collected using a handheld YSI Professional Plus (Yellow Springs, OH).

Water Nutrients and Total Suspended Solids

Surface water samples were collected, filtered, and analyzed for dissolved and particulate nutrients.

*Average variance = $\frac{\sqrt{\sum \sigma_{\bar{x}_1}{}^2 + \cdots + \sigma_{\bar{x}_i}{}^2}}{N^2}$

One gallon cubitainers were rinsed with site water, filled, and then stored on ice in the dark while in the field. Water samples were transported to the lab, processed, and analyzed for turbidity, total suspended solids (TSS), suspended chlorophyll α (fluorometric; non-acidification method), dissolved ammonium+ammonia (NH_x), dissolved nitrate+nitrite (NO_x), soluble reactive phosphorus (SRP), and dissolved organic carbon (DOC). Nitrate-nitrite and ammonium concentrations were determined using an Alpkem 300 segmented flow autoanalyzer with a detection limit of 0.006 and 0.005 mg/L for NO_x and NH_4, respectively (*sensu* Quirk et al. 2015). These data were also analyzed by the Academy of Natural Sciences of Drexel University.

Marsh Resilience to Sea-level Rise

Defining resiliency of a particular marsh to disturbances caused by changes in sea level is generally a complex task. Recent literature has shown, however, that using a suite of known indicators can be used to define and compare the resiliency among marshes (Nagel et al. 2017; Raposa et al. 2016). The Marsh Resilience to Sea-level Rise (MARS; Raposa et al. 2016), a multi-metric index approach to discerning resiliency to rising sea levels, was calculated for the Christina and Broadkill SSIM stations. The MARS index allows for the systematic comparison of marshes, regardless of geomorphic setting. In the future, MARS indices will be calculated for all MACWA SSIM stations, providing a broader context for values reported here for Christina and Broadkill stations.

Results

Elevation Dynamics

Surface Elevation Tables and Marker Horizons

Summary information for each SET at the Christina and Broadkill SSIM stations are provided in Table 3. These data include the benchmark heights taken using RTK GPS, rod depths, and local tidal datums.

At Christina, accretion trends (i.e. from MHs) were significant at SETs 1, 2, and 3, but only cumulative elevation change at SET 2 was significant (Table 4). The lack of statistical significance for cumulative elevation changes for SETs 1 and 3 may be due to the high platform variability (Figure 9). The minimal change in cumulative elevation coupled with high rates of accretion (~6-8 $mm \cdot yr^{-1}$) suggest that shallow subsidence (SS) plays a large role in the change of platform elevations at Christina.

Rates of cumulative surface elevation change and accretion were statistically significant at Broadkill at all SET-MHs (Table 4). Platform variability at Broadkill was low (Figure 10). Cumulative elevation change was typically greater than rates of accretion, yielding negative rates of SS (i.e. expansion of the platform). Negative rates of SS suggest that this station may depend on subsurface biological productivity to compensate for low accretion rates in order to keep pace with sea level rise.

Some variation in cumulative elevation changes may have been due to episodic coastal storms, which could have delivered punctuated sedimentation or prompted platform expansion/contraction. To aid in comparing the effects of storms on platform variability, the dates of major coastal storms

from 2011-2016 which impacted the Delaware Estuary are given (Table 5). Between post-installation days 1269 and 1475 (the winter of 2014-15), all three SETs in Christina experienced a decrease in surface elevation. This reduction may be driven by two factors: 1) a change in SET readers (from the Academy of Natural Science of Drexel University to the Partnership for the Delaware Estuary) and/or b) an extreme winter weather event, specifically Nor'easter Juno (26 January 2015). Storms can cause declines in marsh elevation through erosion and compaction, but positive effects can exist, such as through pulses of sedimentation (Cahoon 2006). Winter storms in freshwater tidal wetlands could also introduce a large volume of salt-laden upland runoff, which could have signficant effects on elevation dynamics and/or vegetation recovery in the spring (e.g. infiltration and storage of salt into marsh soils, salt toxicity to perennial roots or rhizomes). The Delaware State climatological records indicate the highest January precipitation totals since 2007 were those of January 2015 (Office of the Delaware State Climatologist); but in 2016, January precipitation was near average. On the other hand, Broadkill did not see these elevation declines during the same time period, despite experiencing more storm surge during Nor'easter Juno (~0.39 m of surge for 2 days at

Table 3. Description of the surface elevation tables in the Christina and Broadkill SSIM stations.

Station	SET#	Location (Dec. Deg.)		Rod Depth (m)	Receiver Height[1] (m)	Elevations (m NAVD88)			Tidal Amplitude (m)
		Longitude	Latitude			Benchmark[2]	Platform	MSL[3]	
Christina	1	-75.562272	39.720186	11.9	0.215	0.840	0.625		
	2	-75.564328	39.721178	11.6	0.222	0.776	0.554	-0.015	1.63
	3	-75.566078	39.722036	9.5	0.210	0.887	0.677		
Broadkill	1	-75.166033	38.787334	20.1	0.217	0.777	0.560		
	2	-75.168600	38.783920	24.4	0.211	0.685	0.474	-0.121	1.24
	3	-75.169945	38.781103	7.72	0.111	0.566	0.455		

1. Broadkill receiver heights are estimated from pin data; 2. Measured from receiver cap in 2015; 3. NOAA tidal datum from Reedy Point (ID= 8551910), DE for Christina and Lewes (ID= 8557380), DE for Broadkill.

Table 4. Linear model results for each surface elevation table and its respective accretion as derived from marker horizons. SLR = local sea level rise; CE = cumulative elevation change; A= accretion; A_2=2015 reset of marker horizons at Christina; SS = A - CE or shallow subsidence. Significant p-values (<0.05) are bold and italicized.

Station	SET#	Rates ($mm \cdot yr^{-1}$)					Linear Models					
		SLR[1]	CE	A	A_2	SS	CE	p	A	p	A_2	p
Christina	1		2.00	8.65	30.6	6.65	$5.48e^{-3}x+13.2$	0.27	$2.37e^{-2}x+9.40$	***<0.01***	$8.38e^{-2}x-2.56$	0.27
	2	3.54	6.37	8.25	22.4	1.88	$1.74e^{-2}x+19.1$	***<0.01***	$2.26e^{-2}x+14.2$	***<0.01***	$6.13e^{-2}x-1.72$	0.25
	3		2.52	5.96	16	3.45	$6.89e^{-3}x+19.9$	0.22	$1.63e^{-2}x+13.9$	***<0.02***	$4.38e^{-2}x-1.31$	0.26
Broadkill	1		6.5	3.82	-	-2.67	$1.78e^{-2}x+0.812$	***<0.001***	$1.05e^{-2}x+1.09$	***<0.001***	-	-
	2	3.40	6.32	3.98	-	-2.34	$1.73e^{-2}x+7.47$	***<0.02***	$1.09e^{-2}x+1.2$	***<0.001***	-	-
	3		4.23	2.14	-	-2.10	$1.16e^{-2}x-1.51$	***<0.01***	$5.85e^{-3}x+1.3$	***<0.02***	-	-

1. NOAA tidal datum from Reedy Point (ID= 8551910), DE for Christina and Lewes (ID= 8557380), DE for Broadkill

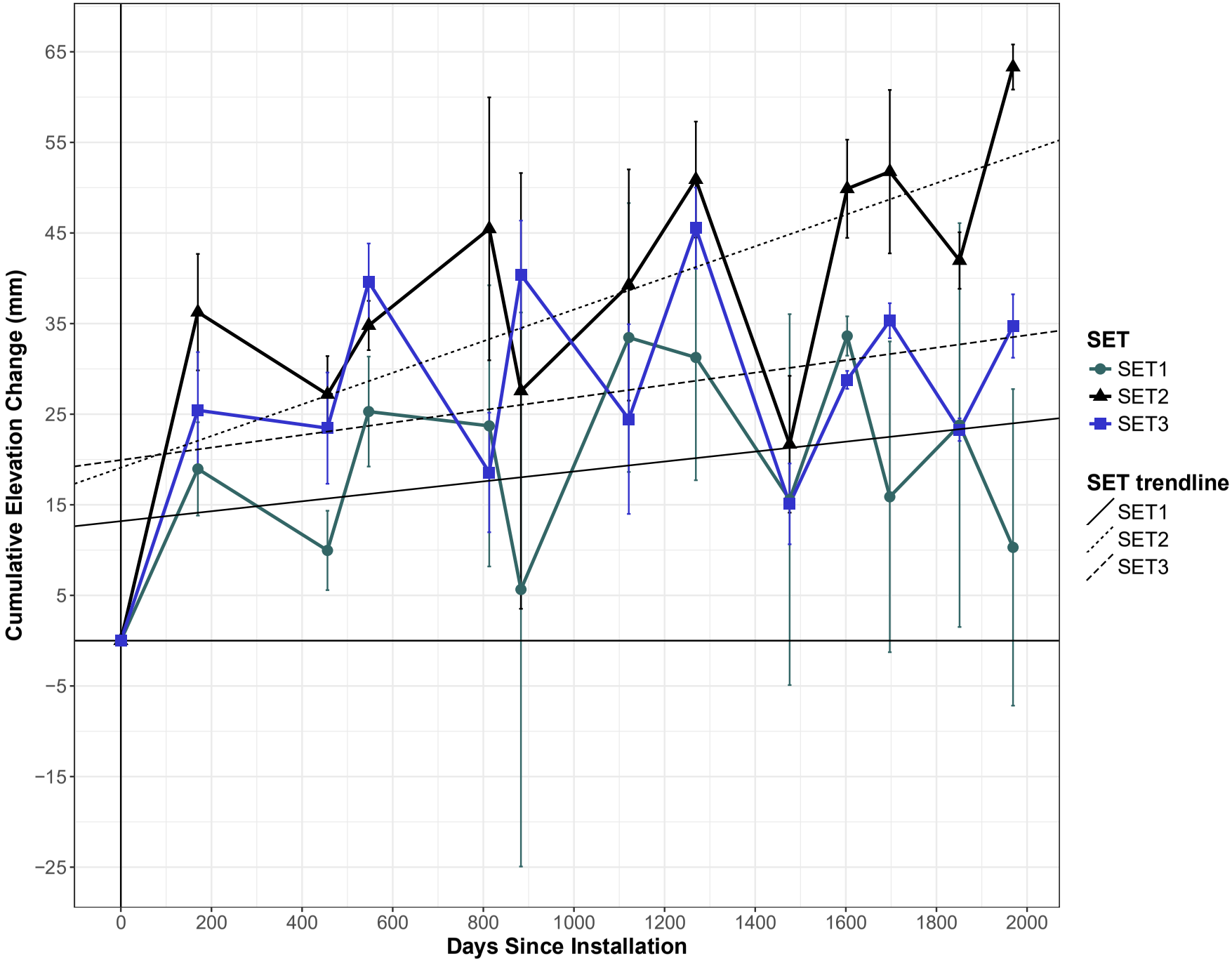

Figure 9. Cumulative elevation changes at Christina River. Error bars are standard errors; trend lines are derived from the respective linear models (Table 4).

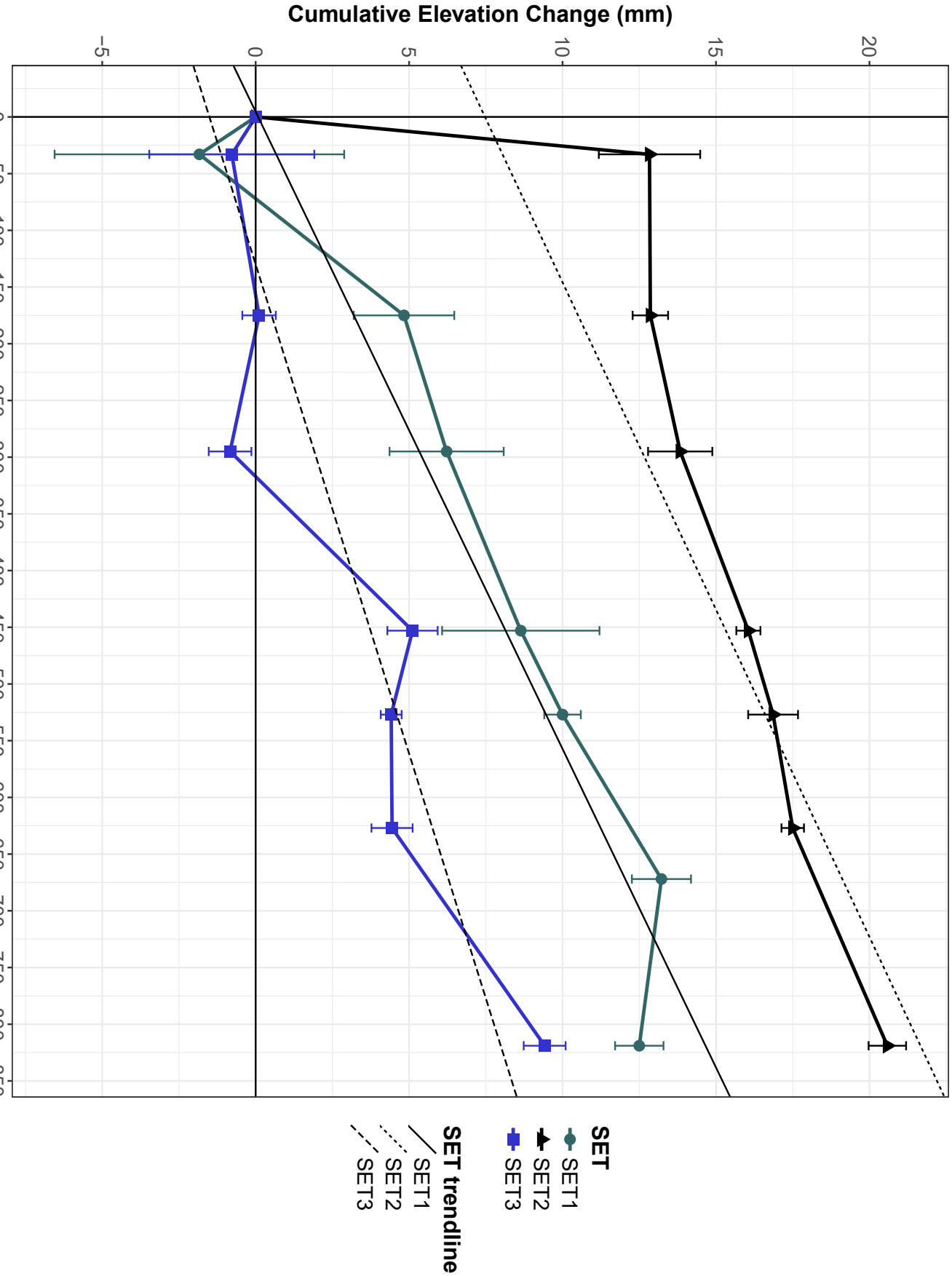

Figure 10. Cumulative elevation changes at Broadkill River. Error bars are standard errors; trend lines are derived from the respective linear models (Table 4).

Table 5. Dates of major coastal storm events which impacted the Delaware Estuary. Dates were translated to the number of days after the SETs were installed at each SSIM station when the storm made landfall in the area.

Event	Calendar Date	Days Since SET Installation	
		Christina	Broadkill
Hurricane Irene	27 Aug. 2011	165	-
Tropical Storm Lee	7 Sept. 2011	176	-
Halloween Nor'easter	29 Oct. 2011	228	-
Hurricane Sandy	29 Oct. 2012	536	-
Nor'easter	10 Oct. 2013	940	-
Winter Storm	14 Feb. 2014	1067	-
Summer Storm	22 May 2014	1164	-
Winter Nor'easter Juno	26 Jan. 2015	1413	243
Tropical Storm Andrea	8 Jun. 2015	1546	376
Nor'easter+Hurricane Joaquin	3 Oct. 2015	1663	672
Winter Nor'easter Jonas	24 Jan. 2016	1776	819

Marcus Hook, PA versus ~0.66 m for three days in Lewes, DE; NOAA tidal datum of predicted vs verified high tide heights).

When compared to rates of local SLR (Table 4), rates of elevation change at SETs 1 and 3 did not keep pace at Christina. Both of these locations, however, had greater elevation capital than SET 2, which has been gaining elevation at an excess of 2.83 $mm \cdot yr^{-1}$ with respect to SLR. Elevation capital can be defined as the elevation extent above a specific datum (e.g. sea level; Cahoon and Gutenspergen 2010). Usually higher elevations experience less sedimentation, but SET 2 accretion rates were comparable to SET 1 and higher than SET 3.

At Broadkill, all SETs gained elevation at rates greater than local SLR. At SET 3, elevation gain was greater than LSLR by 0.83 $mm \cdot yr^{-1}$ and, at SETs 1 and 3, gains were greater than LSLR by ~3 $mm \cdot yr^{-1}$. SET 1 at Broadkill has the greatest elevation capital, followed by SET 2, and SET 3.

Platform Elevation through RTK GPS

Results from ArcMap 3D Analyst analyses of profile elevations for RTK GPS transects can be found in Figure 11 (A-C) for Christina and Figures 12 (A-D) and 13 (A-B) for Broadkill. Maps for each station show the meter zero starting location, or NW Reference (red dots) for each profile transect (Figures 11A for Christina; Figure 12B, 12D, and 13B for Broadkill). All platforms were largely above local sea level (dashed lines in graphics; excluding transect meter zero records within channels); only some areas of the platforms surveyed for both stations were above mean high water.

Platform variability was high around SETs 2 and 3 at Christina (Figure 11C) and no clear trends were observable (linear regressions, $p>0.05$). Around SET 1 (Figure 11B), moving from the point of reference to the end of the transect (left to right in Figure 11A), elevation increased due to the

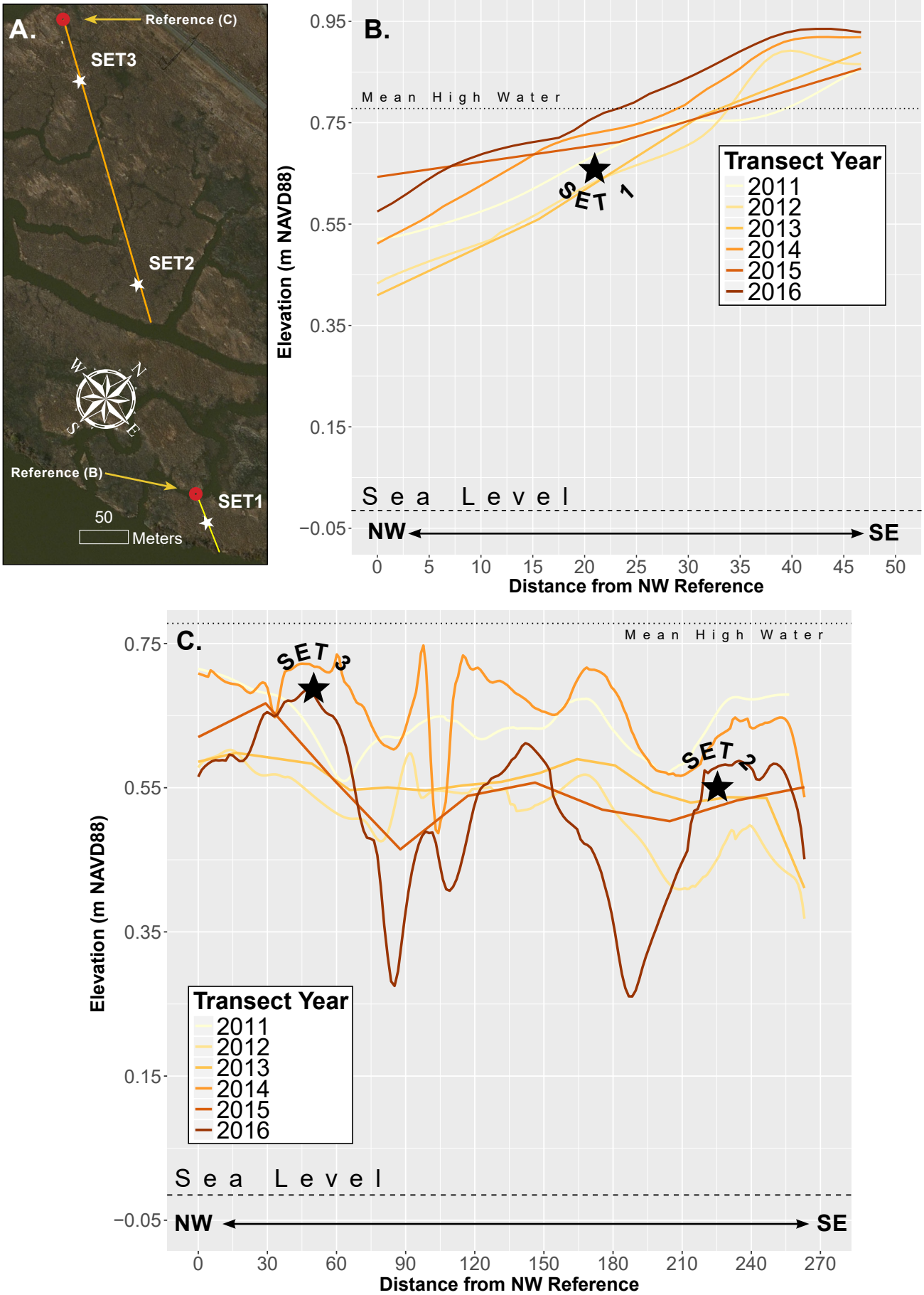

Figure 11. Modeled profile elevations along RTK GPS transects in Christina: A. Map of profiles analyzed; B. Annual profiles at SET 1; C. Profiles from SETs 2 and 3.

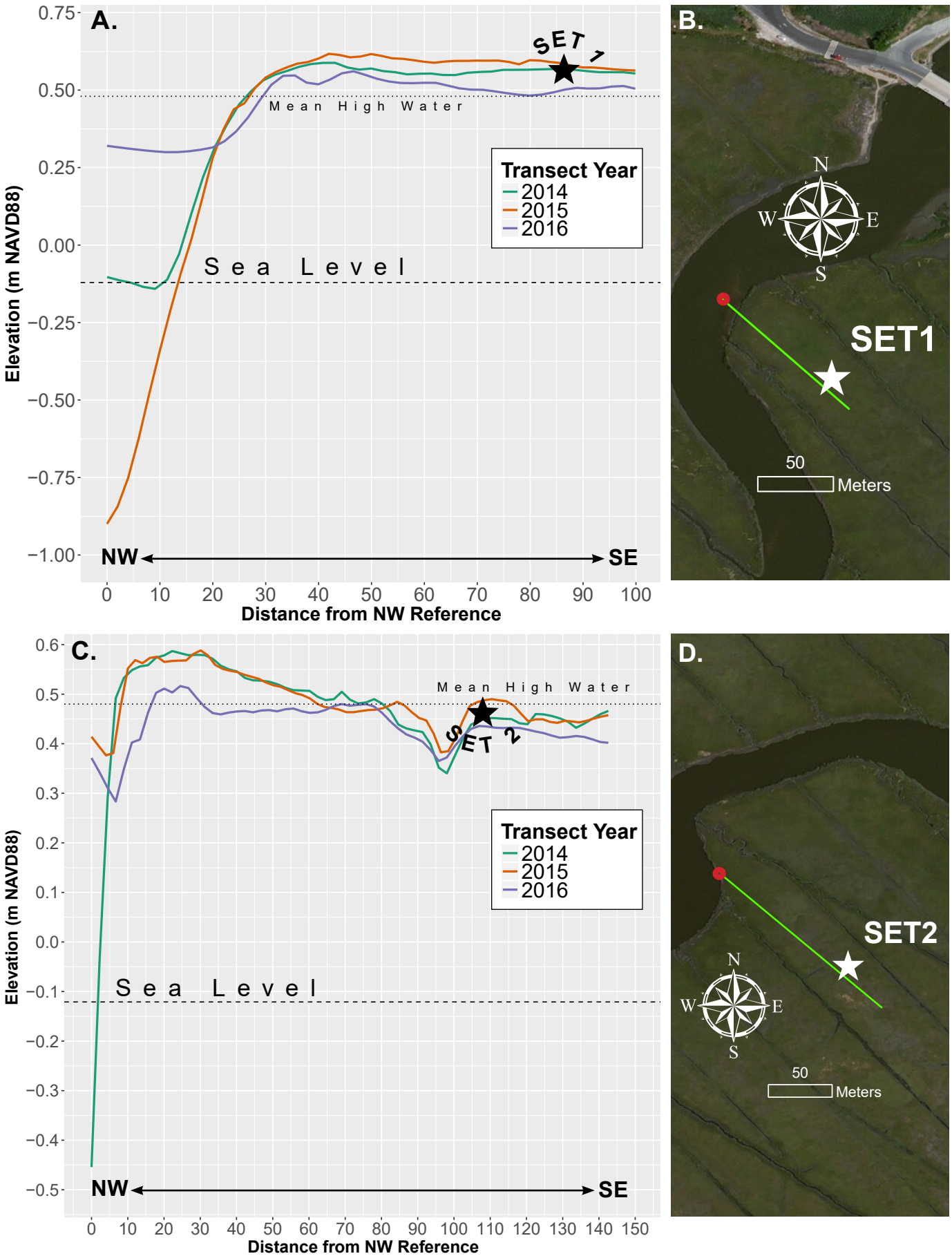

Figure 12. Modeled profile elevations along RTK GPS transects in Broadkill: Annual profiles analyzed for SETs 1 and 2 (A and C, respectively); and maps of profiled transects with NW reference point (red dot) for SETs 1 and 2 (B and D, respectively).

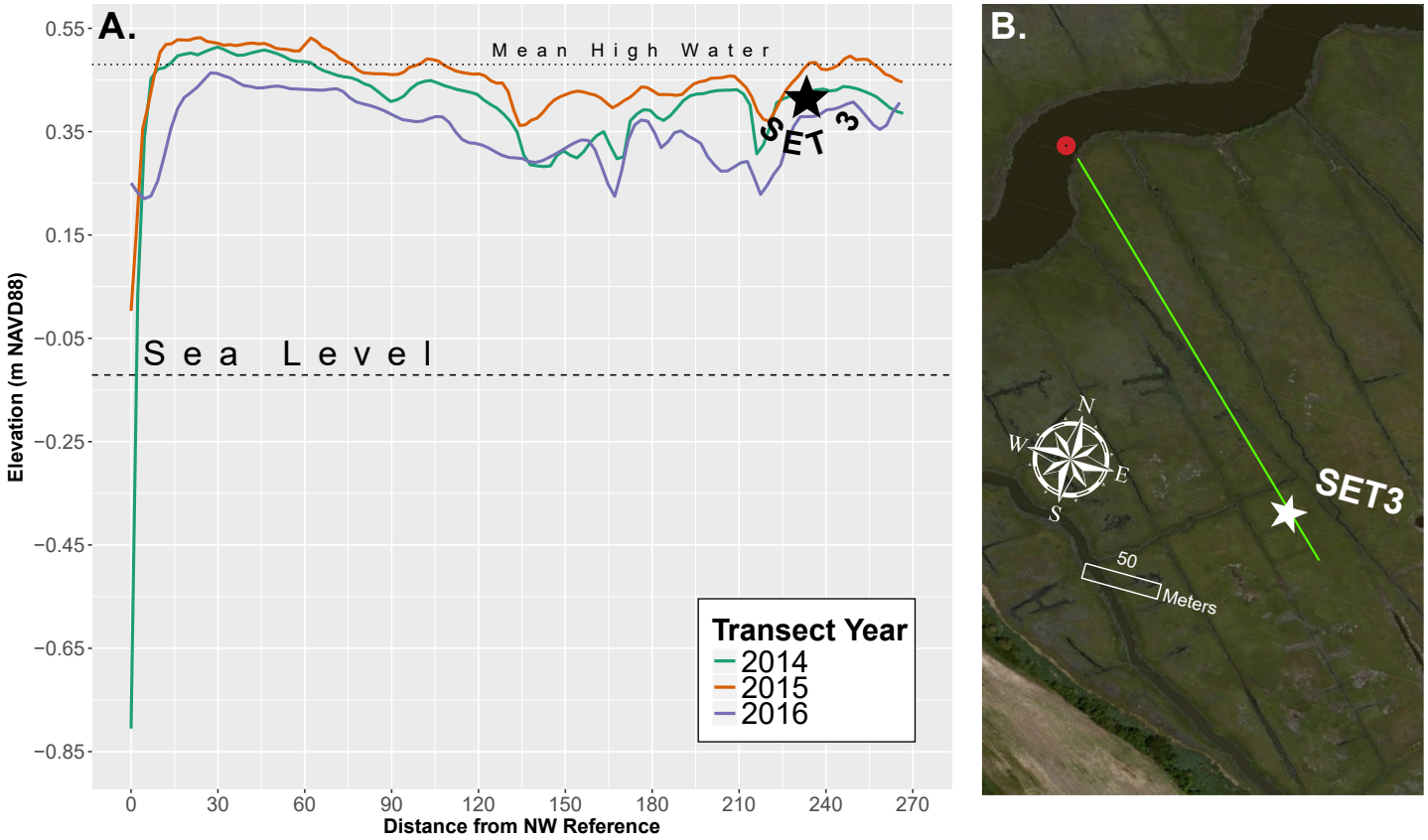

Figure 13. Modeled profile elevations along RTK GPS transects in Broadkill: A. Annual profiles analyzed for SETs 3; and B. Map of profiled transect with NW reference point (red dot) for SETs 3.

Table 6. Mean transect elevation at each A. Christina and B. Broadkill. Standard error in parentheses.

A.	Year	Location	Mean Elevation m NAVD88	N
Christina	2011	SET 1	0.6842 (0.0134)	10
	2012		0.6637 (0.0201)	16
	2013		0.655 (0.106)	17
	2014		0.7431 (0.0191)	24
	2015		0.7851 (0.0275)	15
	2016		0.7821 (0.0198)	27
	2011	SETs 2 and 3	0.6396 (0.00219)	38
	2012		0.5172 (0.00308)	35
	2013		0.5536 (0.0104)	35
	2014		0.6578 (0.00337)	112
	2015		0.5414 (0.00542)	80
	2016		0.5203 (0.00803)	108

B.	Year	Location	Mean Elevation m NAVD88	N
Broadkill	2014	SET 1	0.4268 (0.0374)	95
	2015		0.3762 (0.0595)	59
	2016		0.4602 (0.0134)	24
	2014	SET 2	0.4614 (0.0181)	132
	2015		0.4864 (0.00639)	78
	2016		0.4367 (0.00579)	46
	2014	SET 3	0.4039 (0.0122)	262
	2015		0.4549 (0.00553)	139
	2016		0.3554 (0.00581)	69

berm along the main river bank, likely composed of dredge spoils. Over time, the platform at SET 1 has increased in average elevation (darker colors are more recent than lighter). Regressing these data yielded a significant increasing trend at SET 1 ($y= 0.0228x-45.2$; $p<0.05$; ~0.23 $cm \cdot yr^{-1}$), but it should be noted that the reliability of using surface models generated via RTK surveys to estimate small scale changes (in millimeters) of the marsh platform in response to SLR is low.

Profiles around SETs at Broadkill showed typical marsh features such as a natural berm ~50 m wide followed by platforms lower than mean high water at SETs 2 and SET 3. SET 1 appears to have a relatively consistent platform elevations from marsh edge (i.e. ~15 m after the reference point) to behind the SET. Mean annual transect elevations, derived from raw RTK data, for the Christina and Broadkill SSIM stations are in Table 6.

Vegetation Dynamics

Permanent Vegetation Plots

Blade heights at the Christina SSIM station were highly variable from 2011-2016 (Figure 14). The diversity of plant species in freshwater tidal marshes, and their various growth forms, likely drives this inherent year-to-year variation. Two of the three groups of permanent vegetation plot triplicates did not have a significant trend; near plots, however, had a marginally significant decreasing blade height trend ($p=0.08$).

Fewer years of data were available for Broadkill (Figure 15). Blade height variation and species diversity in salt marshes tend to be lower compared to freshwater tidal marshes, which was observed. Blade heights at mid and far triplicates did not change significantly over time, but blade heights at near triplicates had a marginally significant difference from zero ($p=0.06$).

Species composition was variable at Christina. Since species diversity was high, only the three most dominant species were chosen for statistical analysis: *Typha angustifolia, Peltandra virginica,* and *Impatiens capensis* (Figure 16). In near and far plots (Figure 16A and 16C, respectively), a significant decrease in *T. angustifolia* was observed over time. At near plots, this decrease in *T. angustifolia* was matched by significant increases in both *P. virginica* and *I. capensis*. (all trends $p<0.01$). At far plots, as *T. angustifolia* decreased, *P. virginica* increased significantly ($p<0.01$) and *I. capensis* increased significantly over time ($p<0.05$). At mid plots, *T. angustifolia* cover increased significantly ($p<0.01$), but little change was observed for *P. virginica* ($p=0.08$) and I*. capensis*. The marginally significant increase of blade heights at near plots was probably not due to the presence of typically taller *T. angustifolia*, as its cover decreased over time. The blade height responses may have been due to increased light competition or potentially changing elevations near SET 1 (Figure 11B).

In Broadkill, only two species were observed at permanent vegetation plots: *Spartina alterniflora* and *Distichlis spicata*. At near plots, over the three years of sampling, *D. spicata* increased in cover, whereas *S. alterniflora* decreased (Figure 17A). These trends were not found to be significant. Only *S. alterniflora* was observed at mid plots, and a marginally significant increasing trend in cover was

Figure 14. Change in annual mean blade heights at the Christina SSIM station. Stem measurements were averaged within each plot; triplicate plots were averaged for this graphic. Error bars are standard error (N=3). Linear trends are marginally significant at near plots (p=0.08), but non-significant at mid and far plots.

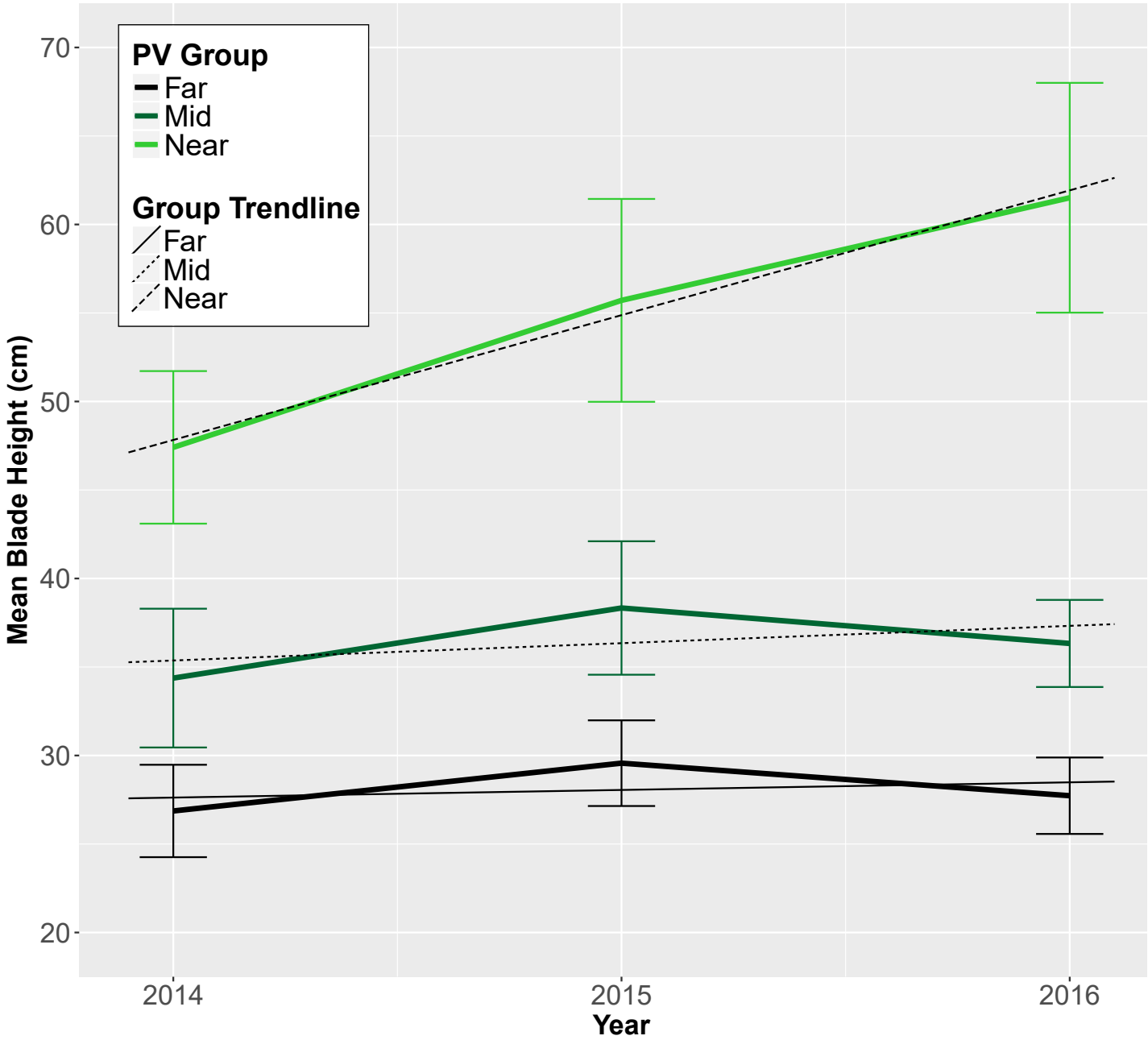

Figure 15. Change in annual mean blade heights at the Broadkill SSIM station. Stem measurements were averaged within each plot; triplicates were averaged for this graphic. Error bars are standard error (N=3). Linear trends are bordering on significant at near plots (p=0.06), but non-significant at mid and far plots.

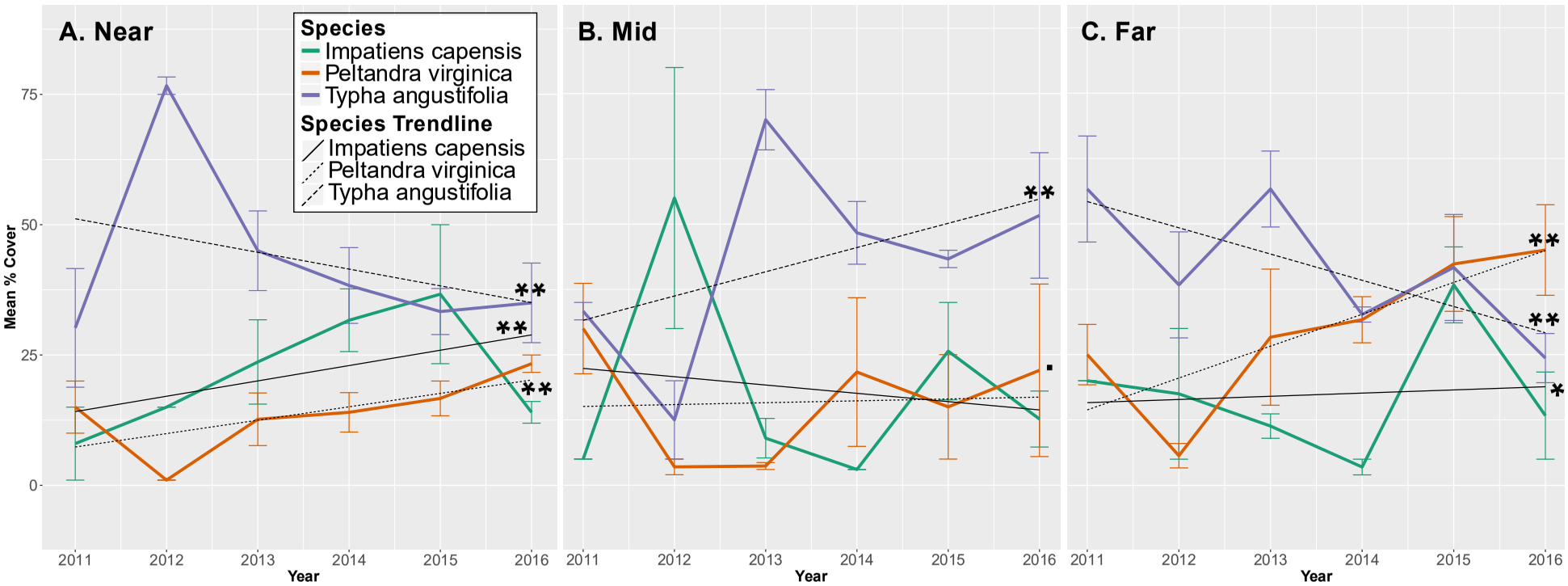

Figure 16. Changes in the annual mean percent cover of the top three dominant plant species at the Christina SSIM station for near (A), mid (B), and far (C) plots. Percent cover estimations were averaged among triplicate plots. Error bars are standard error (N=3). Linear regression results: (·) $p<0.08$, (*) $p<0.05$, (**) $p<0.01$.

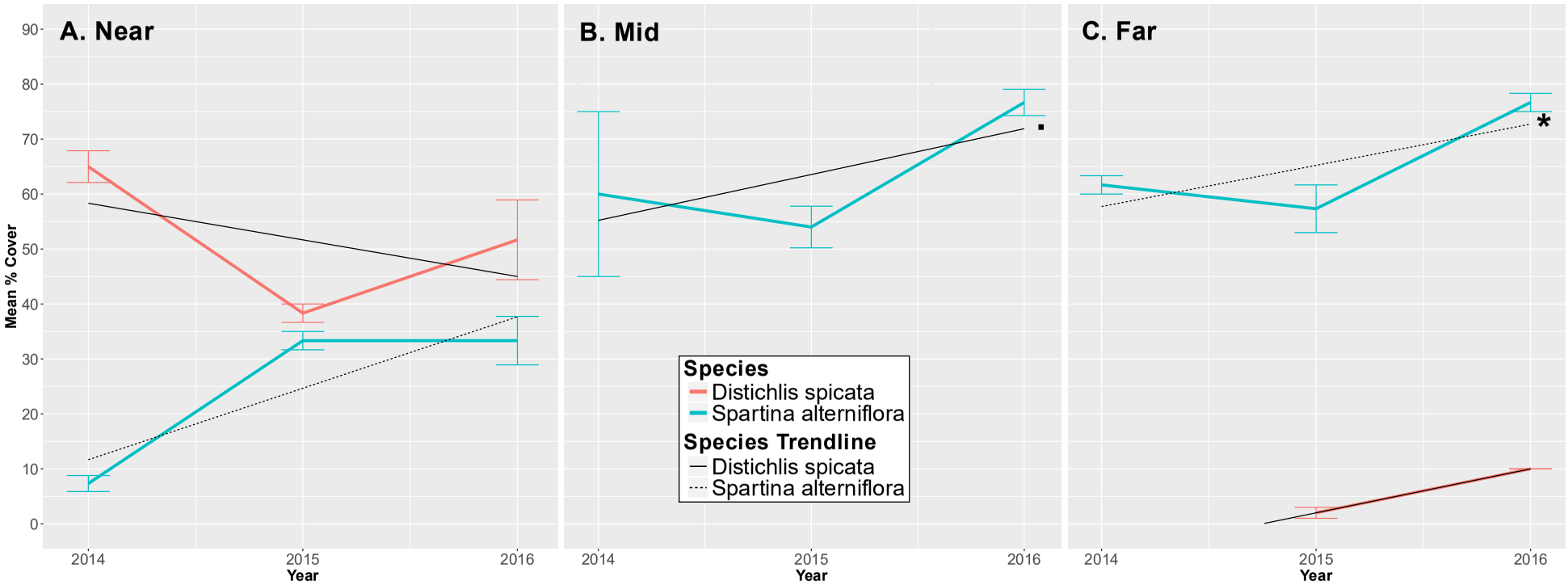

Figure 17. Changes in the annual mean percent cover of the two dominant plant species at the Broadkill SSIM station for near (A), mid (B), and far (C) plots. Percent cover estimations were averaged among triplicate plots. Error bars are standard error. Linear regression results: (·) $p<0.08$, (*) $p<0.05$, (**) $p<0.01$.

observed (Figure 17B). In 2014, no *D. spicata* was observed at far plots, but the following two years it was detected, increasingly, at low percentages (<10%; Figure 17C). This corresponded with a significant increase in *S. alterniflora*.

Plant Productivity

Plant productivity, as measured from biomass, varied from year to year at both SSIM stations. At Christina, aboveground samples were dominated by *Typha angustifolia* but species composition was variable overall across years at both SETs 1 and 3 (Figure 18). The aboveground species community around SET 1 at Broadkill is dominated by *Spartina alterniflora*, followed by *Distichlis spicata* (Figure 19); in 2016, more species typical of high marsh were observed, such as *Spartina patens* and *Salicornia depressa*. At SET 3, aboveground biomass is consisted solely of *Spartina alternfilora*.

From 2010 to 2014, total aboveground biomass at Christina successively decreased, but increased in 2015 (Figure 20A). The relative percent of dead *T. angustifolia* likely drove the increase for 2015, but there is uncertainty as to whether this is site-selection driven or caused by external factors. An analysis of variance among years for each SET yielded no significant differences ($p > 0.1$). Similarly, linear models were also non-significant over time ($p>0.1$).

The date of biomass sampling varied from year to year, so meteorological variables were analyzed to investigate explanatory causes of aboveground biomass not related to sample location selection at Christina. Data from a nearby online personal weather station (ID# KDEWILMI8, obtained from wunderground.com) were downloaded for the months of May, June, and July. Variables included average temperature, maximum daily temperature, cloud cover, and precipitation. Sea level anomalies at Reedy Point Tidal Station (NOAA ID# 8551910) were also investigated for April through July from 2011-2016. Of these, no patterns were discernible from 2011-2015, except cloud cover ($p=0.06$; Figure 21) and perhaps sea level anomalies ($p=0.08$; Figure 22). Precipitation also appeared to increase during this period, but the trend was not significant ($p=0.2$; Figure 21).

Despite observed variation in aboveground productivity at Christina, below ground productivity, although variable, remained in the range of 530-1,010 $g \cdot m^{-2}$, with the exception of SET 1 in 2013 (Figure 20B). Variation in Christina below ground biomass is likely driven by the thick perennial rhizomes of *T. angustifolia*. At SET 1 in 2013, the abundance of below ground biomass was driven by a rhizome of *Peltandra virginica*, which displays patchier distribution than the prolific *T. angustifolia*.

Average variance for aboveground biomass at Christina was 302 $g \cdot m^{-2}$ at SET 1 and 82 $g \cdot m^{-2}$ at SET 3; 201 $g \cdot m^{-2}$ and 78 $g \cdot m^{-2}$ for live material and 194 $g \cdot m^{-2}$ and 51 $g \cdot m^{-2}$ for dead at SETs 1 and 3 respectively. Average variance for total belowground biomass at Christina was 540 $g \cdot m^{-2}$ at SET 1 and 400 $g \cdot m^{-2}$ at SET 3; 532 $g \cdot m^{-2}$ and 319 $g \cdot m^{-2}$ for live material and 255 $g \cdot m^{-2}$ and 109 $g \cdot m^{-2}$ for dead at SETs 1 and 3 respectively. Average variance for 0-15 cm depth belowground biomass was 484.9 $g \cdot m^{-2}$ at SET 1 and 428.5 $g \cdot m^{-2}$ at SET 3; for 15-30 cm depth variance was 699.9 $g \cdot m^{-2}$ at SET 1 and 254.5 $g \cdot m^{-2}$ at SET 3. For live materials, 0-15 cm, variance was 606.7 $g \cdot m^{-2}$ and 487.9

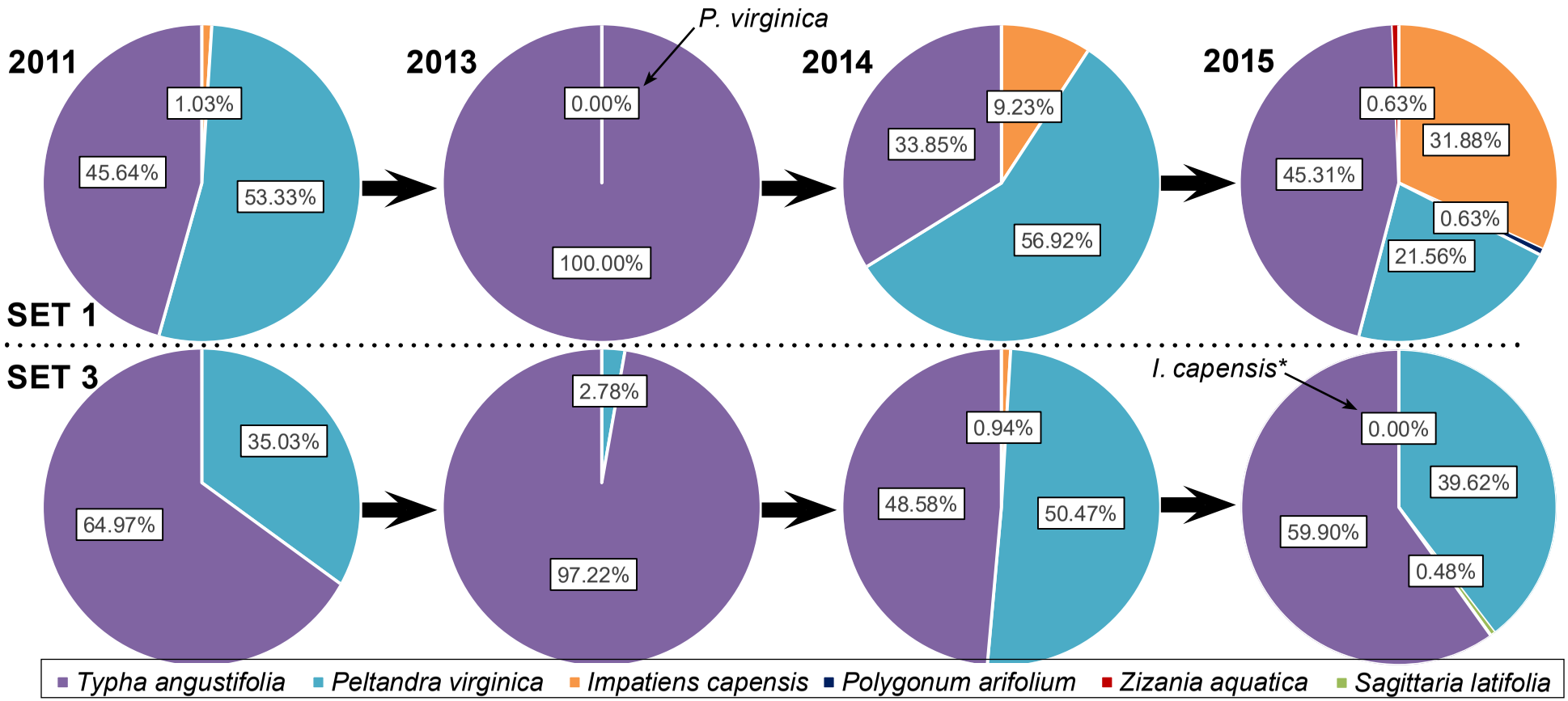

Figure 18. Changes in species composition at the Christina SSIM station based on stem densities from triplicate plots above ground biomass samples from SETs 1 and 3. **I. capensis* was present (at >0%), but no densities were obtained because stems were broken.

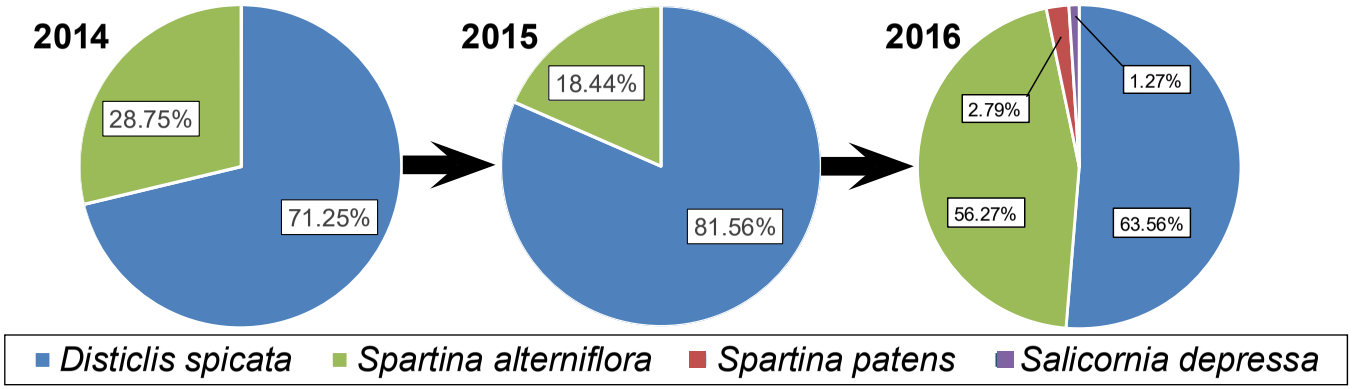

Figure 19. Changes in species composition at the Broadkill SSIM station according to stem density data from SET 1; only *Spartina alterniflora* occurred at SET 3 all three survey years.

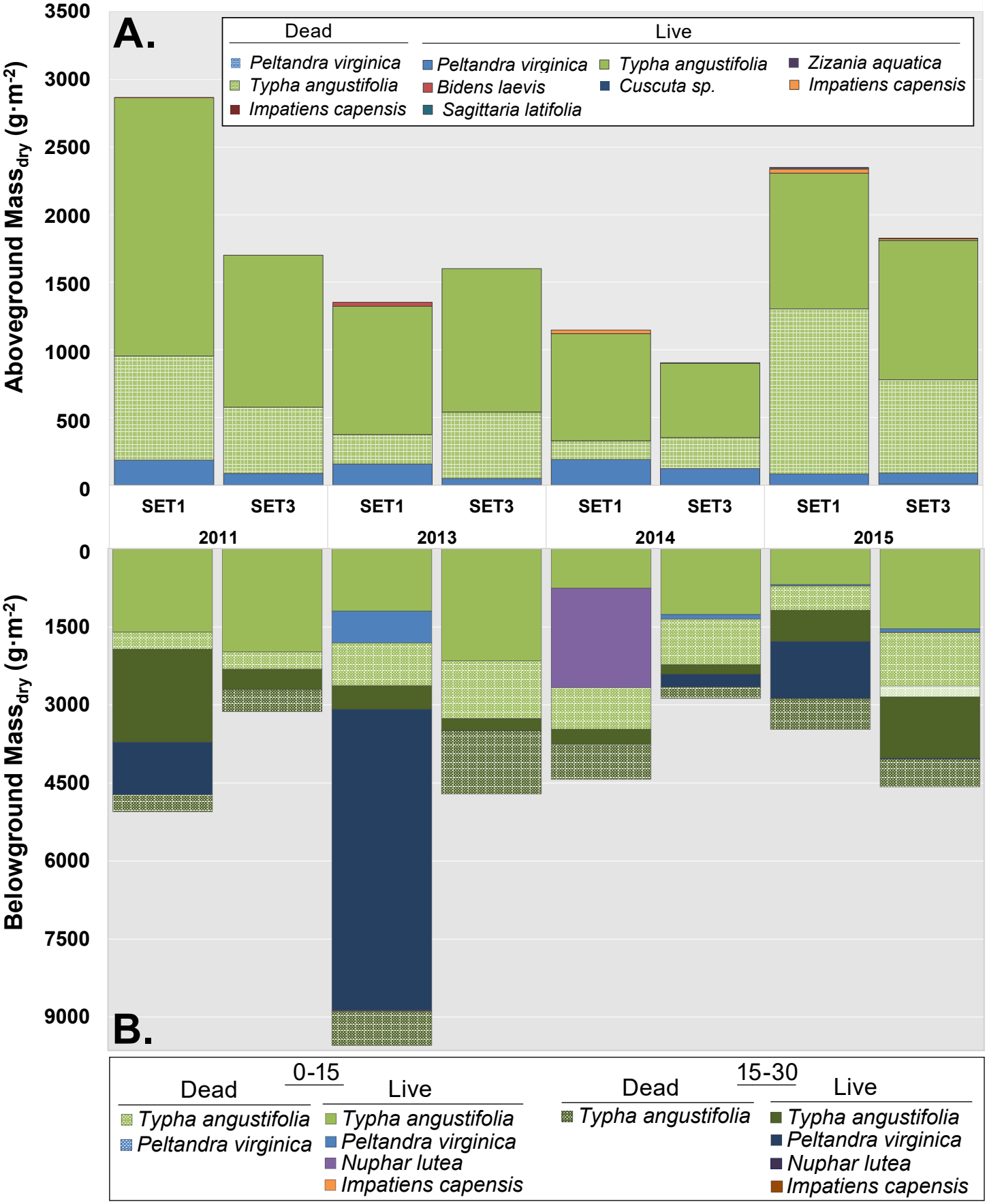

Figure 20. Average above (A) and below (B) ground biomass for Christina across sampling years.

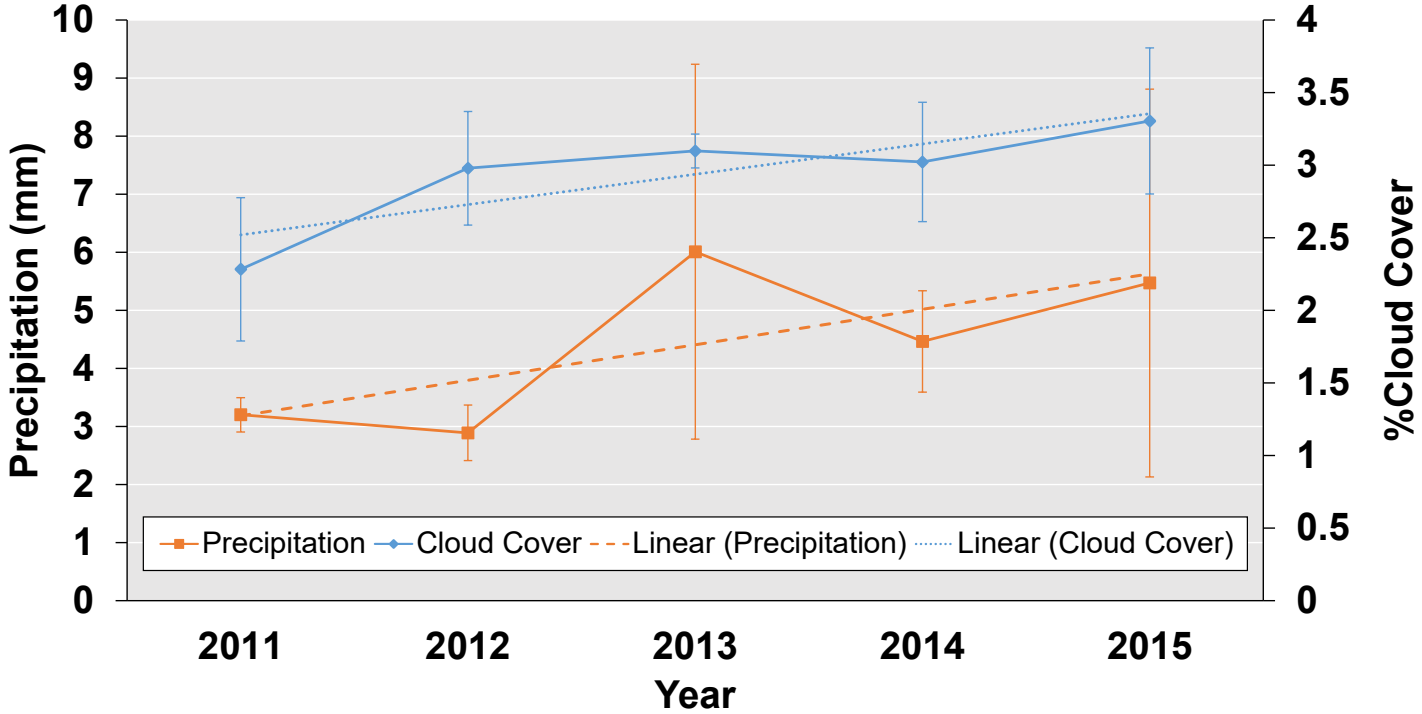

Figure 21. Average spring (May, June, July) precipitation (R^2=0.50) and cloud cover (R^2=0.72) from a Wilmington, DE online Personal Weather Station (PWS; courtesy of www.wunderground.com). Error bars are standard error (N=3). Aside from year-to-year variation caused by site choice, the decreasing trend in aboveground biomass at Christina may have resulted from such trends in weather variables..

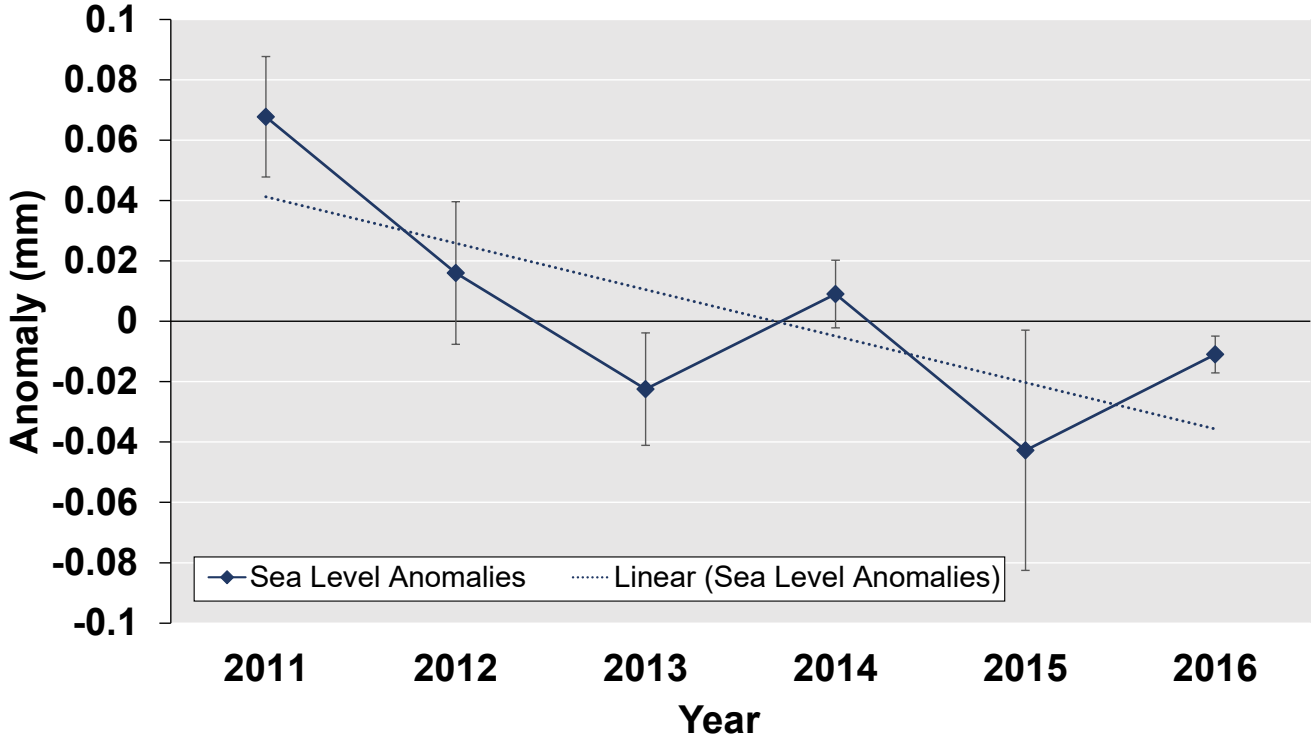

Figure 22. Average spring (April, May, June, July) sea level anomalies (R^2=0.56) from Reedy Point Tidal Station, DE (NOAA tidal datum, ID= 8551910). Error bars are standard error (N=4).

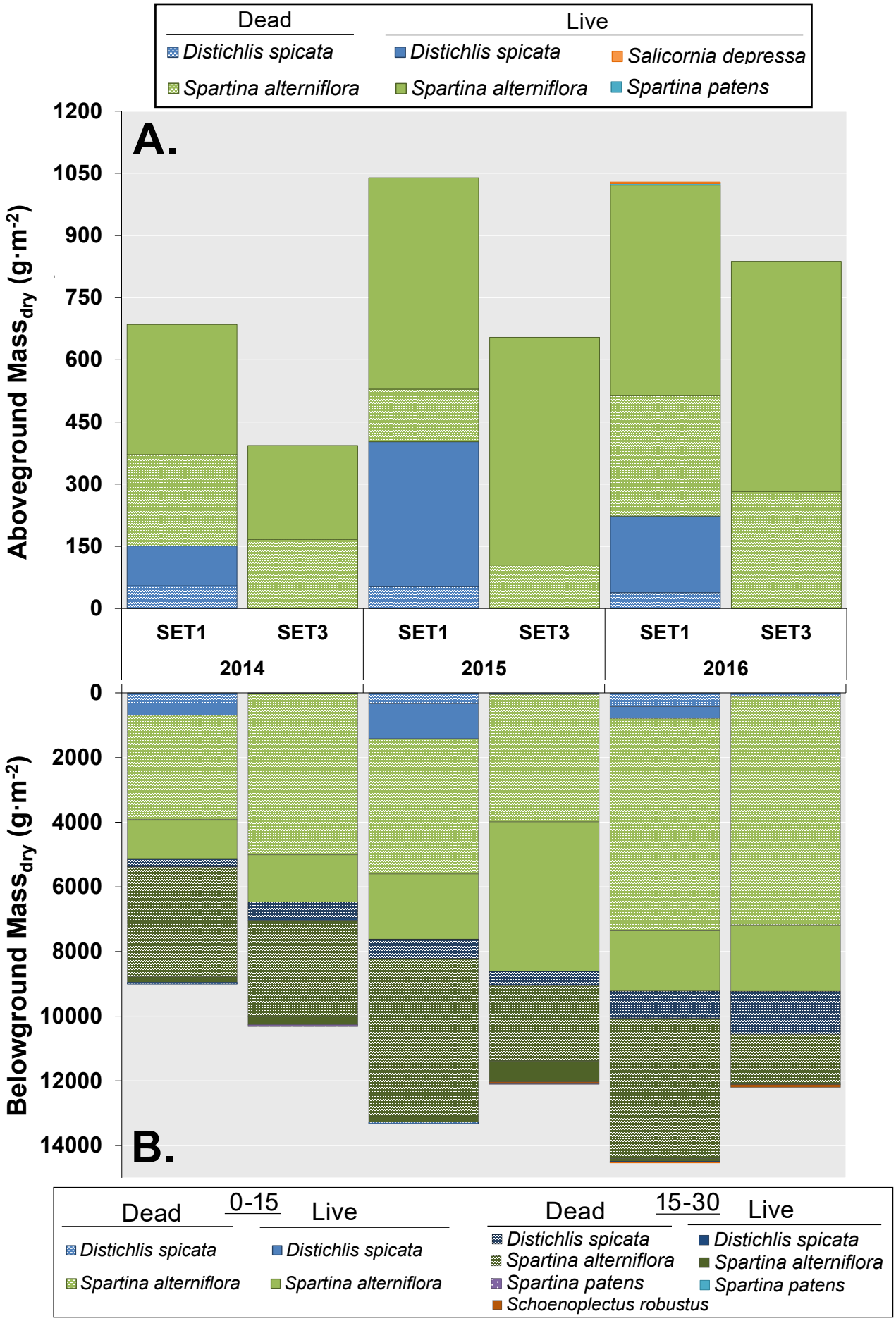

Figure 23. Average above (A) and below (B) ground biomass for Broadkill across sampling years.

$g \cdot m^{-2}$ for SETs 1 and 3, respectively; 15-30 cm, variance was 862.2 $g \cdot m^{-2}$ and 270.1 $g \cdot m^{-2}$ for SETs 1 and 3, respectively. For dead materials, 0-15 cm, variance was 191.6 $g \cdot m^{-2}$ and 192.8 $g \cdot m^{-2}$ for SETs 1 and 3, respectively; 15-30 cm, variance was 203.2 $g \cdot m^{-2}$ and 182.4 $g \cdot m^{-2}$ for SETs 1 and 3, respectively.

For aboveground biomass at Broadkill, samples extracted near SET 3 had no species composition changes, but had marginally increasing total biomass ($p=0.06$; Figure 23). This variability may have been inherent and related to sample location. At SET 1, despite some species composition change, there was no significant change in total biomass over time ($p>0.1$). More data are necessary to investigate potential cause-effect relationships at Broadkill.

Average variance for aboveground biomass at Broadkill was 55.9 $g \cdot m^{-2}$ at SET 1 and 39.8 $g \cdot m^{-2}$ at SET 3; 60.3 $g \cdot m^{-2}$ and 27.5 $g \cdot m^{-2}$ for live material, and 19.6 $g \cdot m^{-2}$ and 19.8 $g \cdot m^{-2}$ for dead at SETs 1 and 3 respectively. Average variance for total 0-15 cm depth below ground biomass at Broadkill was 150.9 $g \cdot m^{-2}$ at SET 1 and 144.4 $g \cdot m^{-2}$ at SET 3; for 15-30 cm depth variance was 102.8 $g \cdot m^{-2}$ at SET 1 and 79.7 $g \cdot m^{-2}$ at SET 3. For live materials, 0-15 cm, variance was 37.7 $g \cdot m^{-2}$ and 90.2 $g \cdot m^{-2}$ for SETs 1 and 3, respectively; 15-30 cm, variance was 10.2 $g \cdot m^{-2}$ and 56.3 $g \cdot m^{-2}$ for SETs 1 and 3, respectively. For dead materials, 0-15 cm, variance was 93.6 $g \cdot m^{-2}$ and 113.1 $g \cdot m^{-2}$ for SETs 1 and 3, respectively; 15-30 cm, variance was 125.3 $g \cdot m^{-2}$ and 101.9 $g \cdot m^{-2}$ for SETs 1 and 3 , respectively.

Soil Quality

Several soil quality metrics varied with depth at the Christina SSIM station. As deeper portions of the core represent earlier time periods, such variations may imply subsequent changes in environmental conditions over time. At Christina, both sampling locations (SETs 1 and 3) had decreasing percent nitrogen (N; Figure 24) and percent organic matter with depth (Figure 26), but increasing bulk density (Figure 24), and percent solid material (Figure 26) with depth. Percent phosphorous (P) from 5 to 30 cm depths ranged, on average, from 0.08 to 0.13%, but exceeded 0.15% in the first 3 cm (Figure 25). These departures suggest that N availability increased over time with a recent increase in P, but other aspects of soil structure decreased (organic matter, bulk density, etc...). Percent carbon and soil carbon density, however, were relatively consistent with depth (Figures 26 and 25, respectively). The changes in N and P may have consequences for plant productivity, which may affect soil bulk densities and carbon storage in the future. An inverse relationship between percent organic matter and percent solid materials suggested increasingly minerogenic materials with depth.

At Broadkill, there was less variation in soil quality metrics with depth, as compared to Christina (Figures 27-29). Of note is a similar recent increase in percent phosphorous (Figure 28). Differences between SET sampling sites, however, were more observable. Soils from SET 1 had higher solid

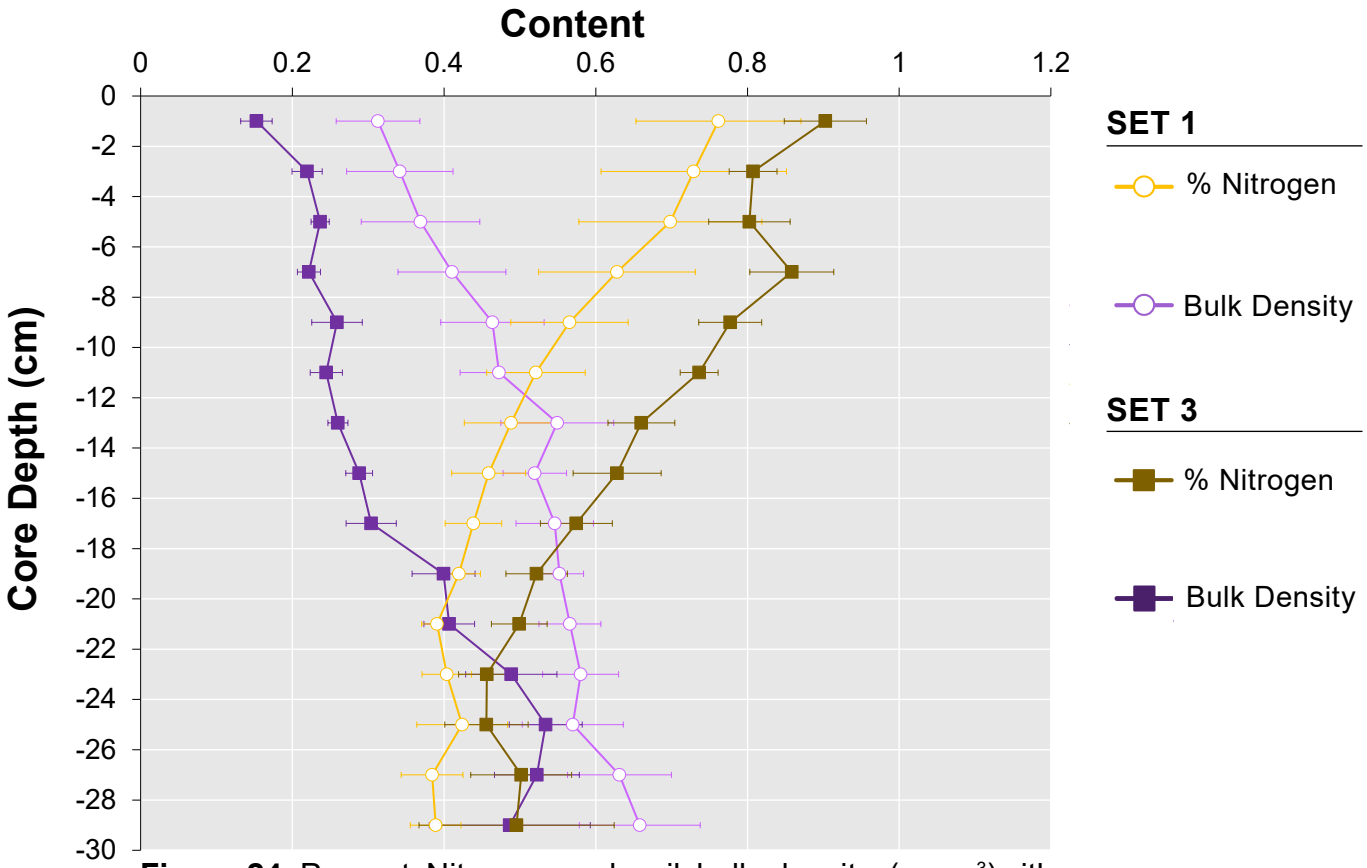

Figure 24. Percent Nitrogen and soil bulk density (g·cm^{-3})with depth at soil cores exacted from SETs 1 (hollow circles) and 3 (dark squares) from 2014-15 at Christina. Error bars are standard error across sampling dates (N=2).

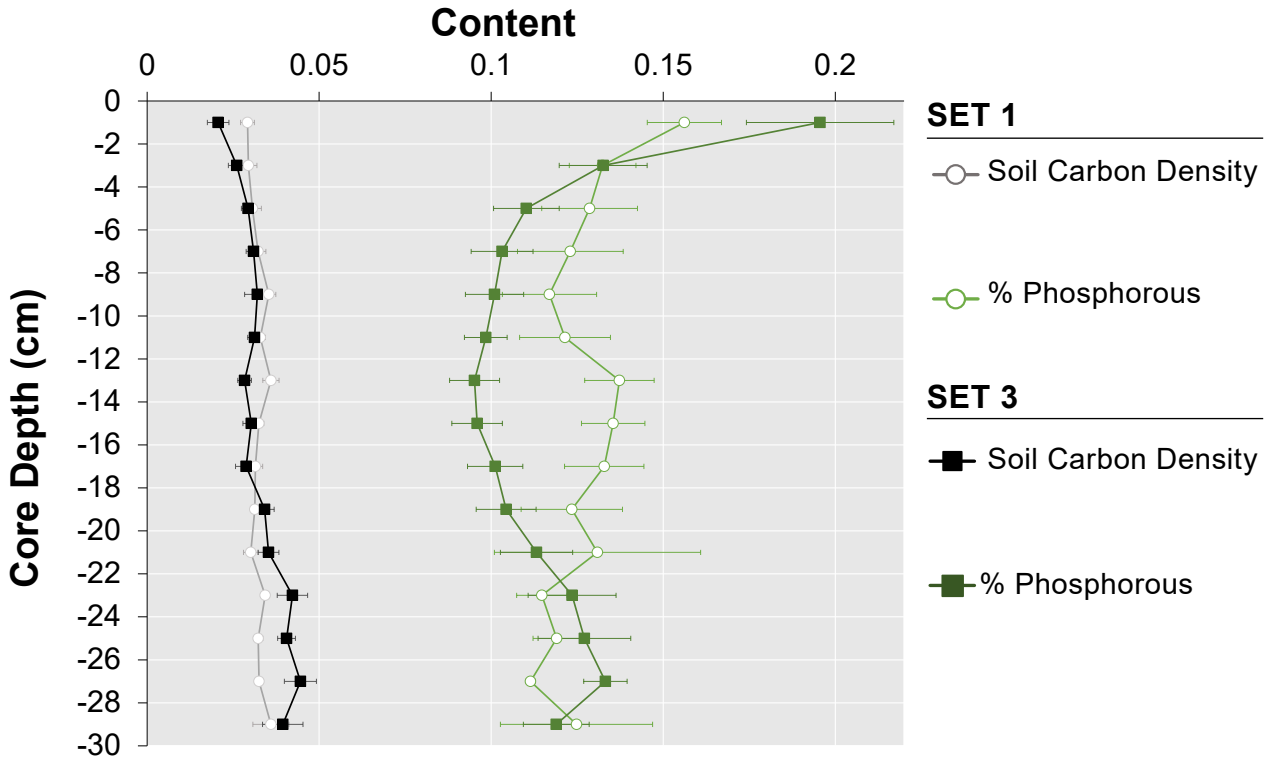

Figure 25. Soil carbon density (g·cm^{-3}) and percent Phosphorous with depth at soil cores exacted from SETs 1 (hollow circles) and 3 (dark squares) from 2014-15 at Christina. Error bars are standard error across sampling dates (N=2).

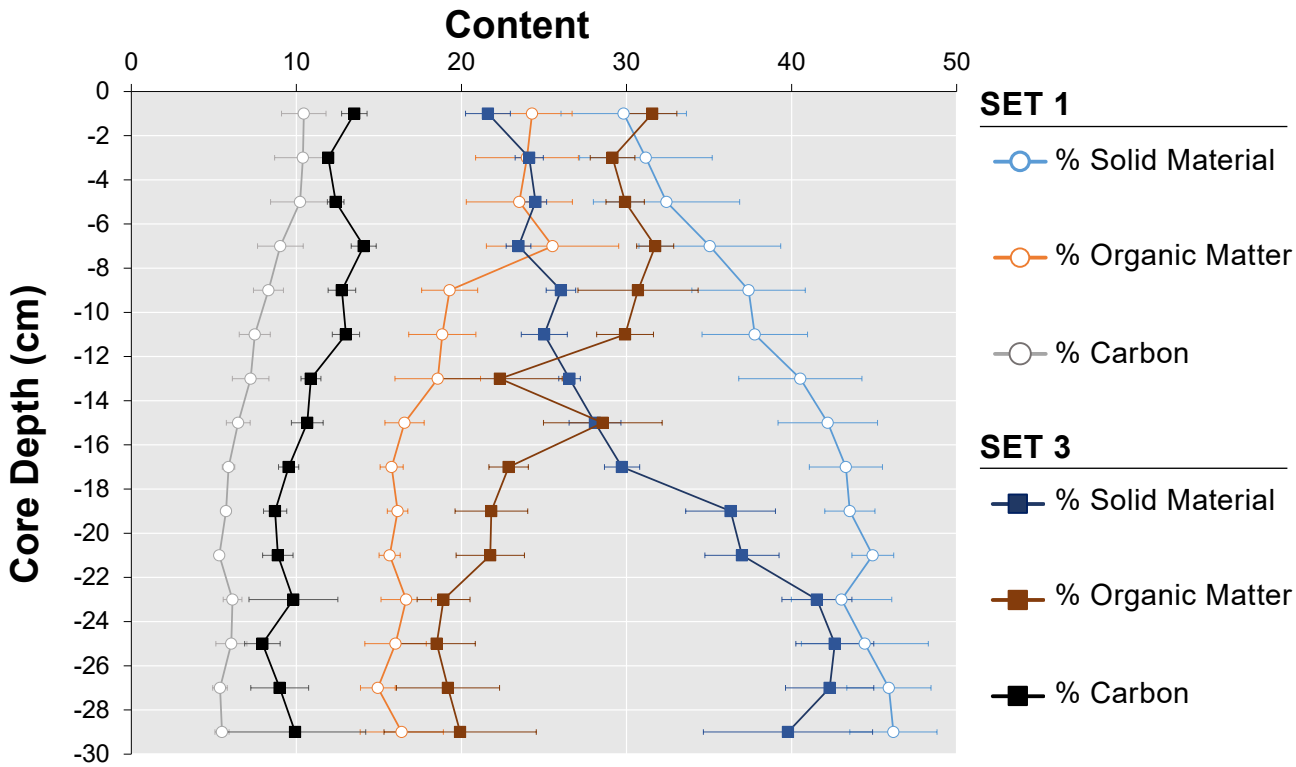

Figure 26. Percent soil material (1-%water content), percent organic matter, and percent Carbon with depth from SETs 1 (hollow circles) and 3 (dark squares) from 2014-15 at Christina. Error bars are standard error across sampling dates (N=2).

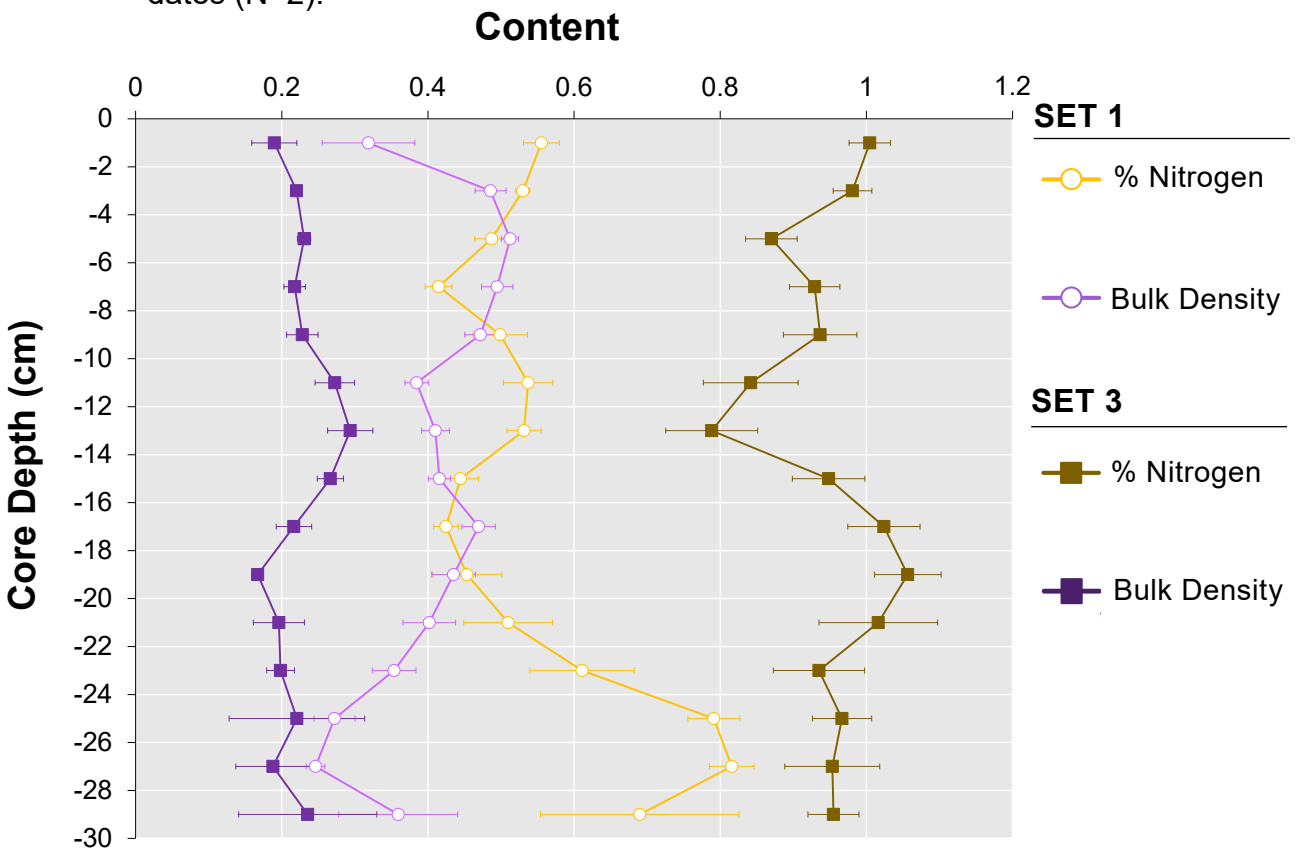

Figure 27. Percent Nitrogen and soil bulk density ($g \cdot cm^{-3}$) with depth at soil cores exacted from SETs 1 (hollow circles) and 3 (dark squares) from 2014-15 at Broadkill. Error bars are standard error across sampling dates (N=2).

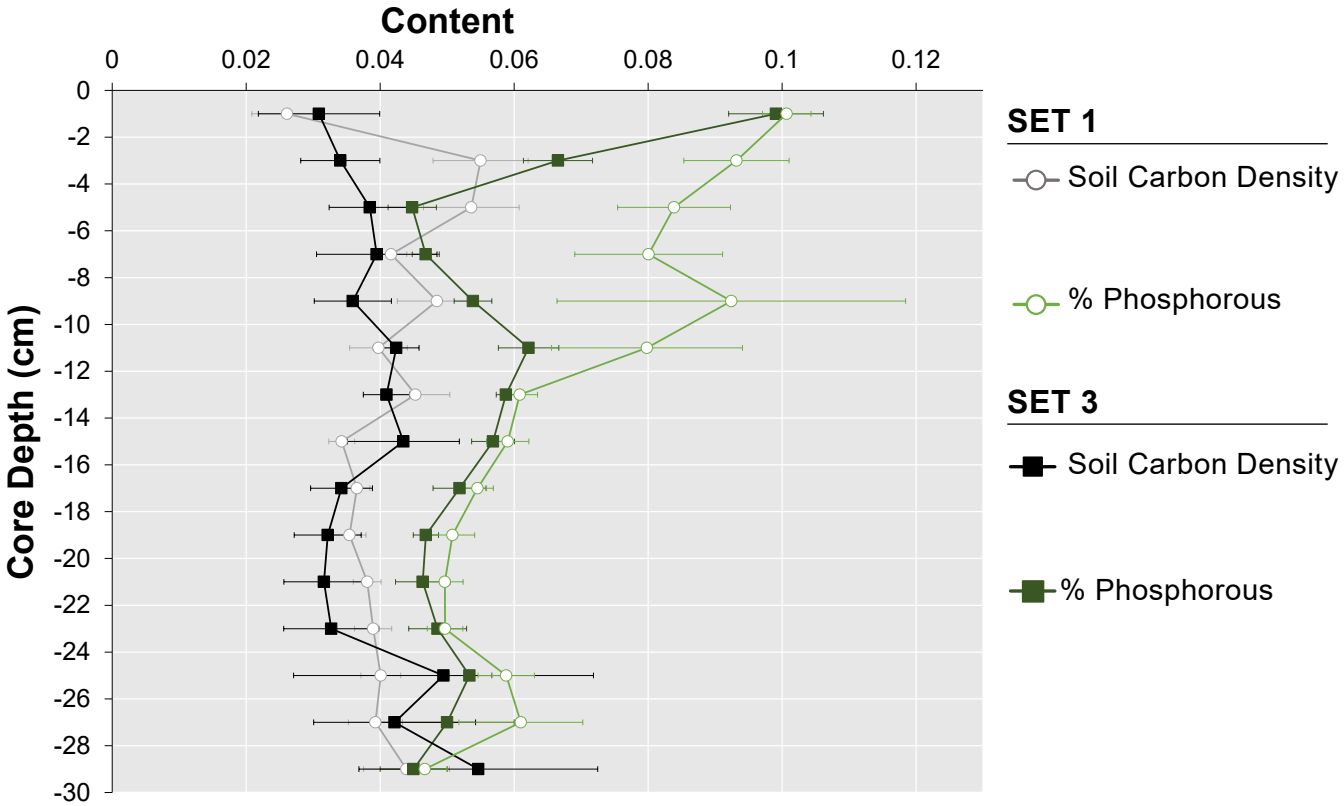

Figure 28. Soil carbon density ($g \cdot cm^3$) and percent Phosphorous with depth at soil cores exacted from SETs 1 (hollow circles) and 3 (dark squares) from 2014-15 at Broadkill. Error bars are standard error across sampling dates (N=2).

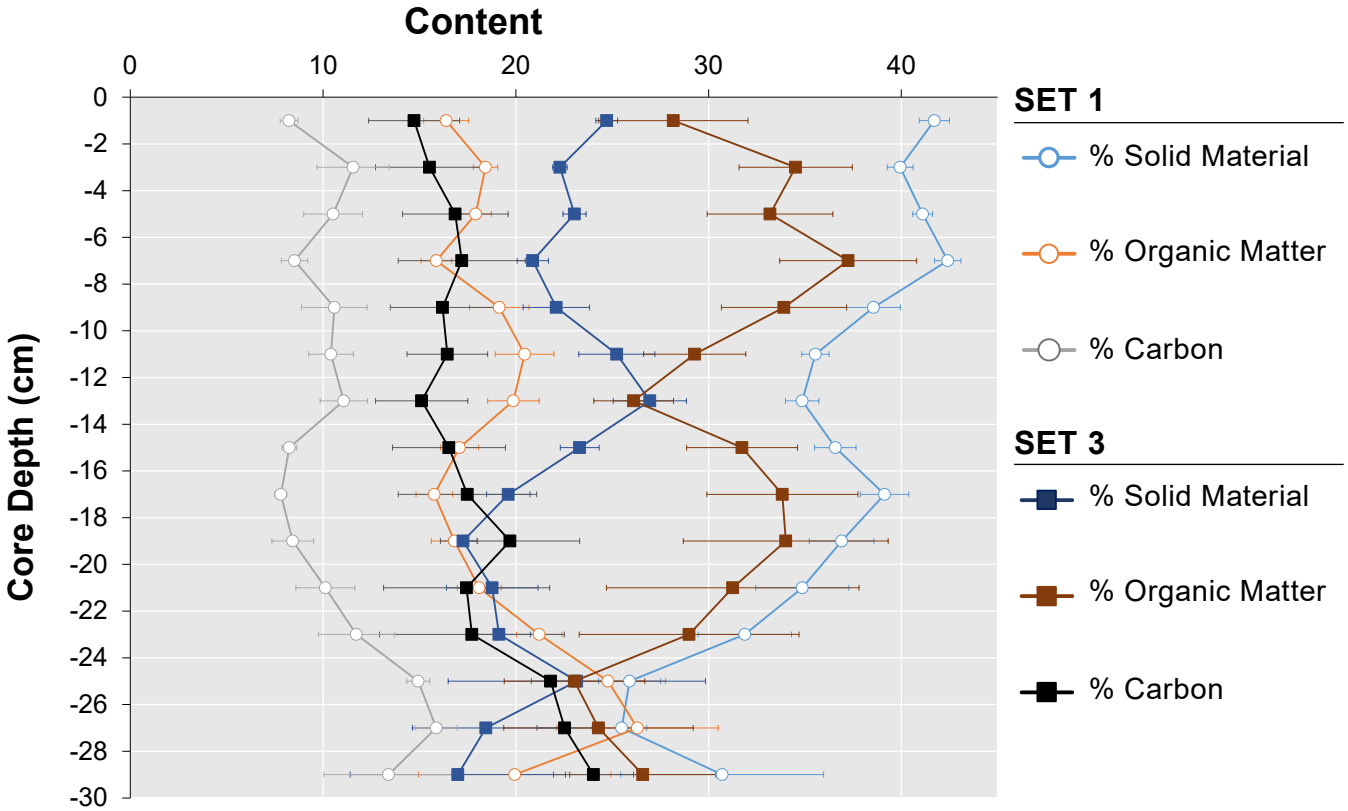

Figure 29. Percent soil material (1-%water content), percent organic matter, and percent Carbon with depth from SETs 1 (hollow circles) and 3 (dark squares) from 2014-15 at Broadkill. Error bars are standard error across sampling dates (N=2).

material content (Figure 29) and bulk density (Figures 27), but lower percent organic matter (Figure 29), percent carbon/soil carbon density (Figures 29 and 28, respectively), and percent nitrogen (Figure 27) than SET 3. A relationship with solid material and organic matter exists at Broadkill similar to Christina (Figure 9). However, SET 1 appears to have a higher mineral content than SET 3 overall.

Water Quality

Water quality spot sampling results were variable. Hence, temporal or spatial trends were not analyzed. Salinity levels averaged 0.36 ppt at Christina and 26 ppt at Broadkill (Table 7). At both sites, pH was generally neutral, and dissolved oxygen (DO) levels were relatively high. Seasonal variation is expected in DO, but more data is needed to discern if seasonal fluctuations are changing through time or driven by other factors (e.g. nutrients). This may also be the case for chlorophyll α and aqueous nutrients (nitrogen, phosphorous, and carbon).

Table 7. Water quality metrics obtained for Christina from 2010-2016 and Broadkill from 2014-2016. Standard errors in parenthesis.

	Metric (units)	Christina		Broadkill	
		Mean	N	Mean	N
Water Quality via YSI	Temperature (°C)	20 (1)	82	17.3 (1.4)	30
	Salinity (ppt)	0.36 (0.05)	80	26.0 (0.9)	30
	Dissolved Oxygen ($mg \cdot L^{-1}$) {%}	7.55 (0.26) {80.7}	76	6.28 (0.49) {72.4}	30
	pH	7.4 (0.06)	67	7.68 (0.12)	30
	Total Dissolved Solids ($mg \cdot L^{-1}$)	532 (49)	25	26400 (920)	30
Water Nutrients via Grab Sampling	Total Alkalinity ($mg \cdot L^{-1}$)	52.2 (1.0)	85	94.6 (2.0)	25
	Dissolved Organic Carbon ($mg \cdot L^{-1}$)	11.3 (2.2)	65	2.25 (0.24)	25
	Chlorophyll α ($ug \cdot L^{-1}$)	22.9 (2.7)	85	25.7 (2.6)	25
	Soluble Reactive Phosphorous ($mg \cdot L^{-1}$)	0.0199 (0.0017)	85	0.0187 (0.0027)	25
	Ammonia (uM)	4.31 (0.64)	85	4.91 (0.58)	25
	Ammonium ($mg \cdot L^{-1}$)	0.0604 (0.0089)	85	0.0132 (0.0081)	25
	Nitrate-Nitrite ($mg \cdot L^{-1}$)	1.40 (0.055)	85	0.115 (0.029)	25
	Total Suspended Solids ($mg \cdot L^{-1}$)	20.3 (1.1)	85	49.5 (3.9)	25

Marsh Resilience to Sea Level Rise

Marsh Resilience to Sea Level Rise (MARS) scores (Raposa et al. 2016) were 4.0 and 5.0 (5 is lowest risk) for Christina and 3.4 and 3.7 (5 is lowest vulnerability) for Broadkill (Table 9; value ranges for assigning scores is in Appendix II). The MARS risk score is the number of metrics which fell above 3.0, which summarizes the extent of potential sensitivity to sea level rise (5 is lowest risk). The MARS ratio is the elevation change divided by sea level trends, which was 1.03 and 1.65 for Christina and Broadkill, respectively. Ratios near 1 suggest change rates are comparable to sea level rise rates. As a point of comparison, in the Raposa et al. (2016) MARS publication, the St. Jones Reserve, located in Dover, DE, midway between the Christina and Broadkill SSIM stations along the Delaware Coast, scored 4, 3.6, and 1.2 for the MARS risk, average, and ratio indices, respectively.

Table 8. MARS scores and indices for Christina and Broadkill SSIM stations. A score of 1 is indicates the highest vulnerability (red; lowest vulnerability of 5 in green bold).

Metric	Christina		Broadkill	
	Raw Value	Score	Raw Value	Score
Percent of marsh below MHW	94.1	1	84.9	1
Percent of marsh in lowest third of elevation range	6.7	**5**	6.5	**5**
Skewness	-2.2	**5**	-1.1	4
Elevation change	3.65	3	5.6	**5**
Short-term accretion rate	7.6	**5**	3.3	3
Long-term accretion rate	7.9*	**5**	4.7**	4
Total Suspended Solids	19.7	2	59	**5**
Tidal Range	1.8	4	1.24	3
Long-term rate of sea level rise	3.54	1	3.40	2
Short-term variation in water levels	4	4	1	4

Indices	Christina	Broadkill
Risk	3	3
Average	3.43	3.67
Ratio	1.03	1.65

*From Velinsky et al. 2010; **From Church et al. 1981

Discussion

One of the main questions that SSIM LTM seeks to answer is whether the marsh is keeping pace with sea level rise. Since this function is governed by a suite of factors, many characteristics were monitored through time to better understand site specific influences and marsh elevation maintenance.

Direct monitoring of elevation dynamics at SSIM stations, via SET-MH, showed that two of the three SETs at Christina were not keeping pace with sea level, despite ample accretion determined via MH. The study marshes in Christina also do not have significant elevation capital (RTK surveys), because much of the platform is below mean high water, especially at SETs 2 and 3. At Broadkill, SET-MHs are keeping pace with local sea level, but SETs 2 and 3 have tracts of high marsh that are below mean high water, which may lead to prolonged flooding of these areas. Coastal wetlands up the estuarine gradient may more regularly experience impacts to elevation dynamics from upland run off than from storm surge. Understanding those dynamics may be critically important in better understanding the long term viability of freshwater tidal wetlands to sea level rise and climate change, especially those adjacent to urban areas.

The purpose of collecting blade height data is to track potential changes in vegetation morphology related to hydrology and sea level. Morphological changes caused by increased inundation are well known for *Spartina alterniflora*, but less is known about these responses in freshwater tidal marsh vegetation. At Broadkill, only near permanent vegetation plots had increases in plant height, which were coupled by a shift in species dominance from *Distichlis spicata* to *S. alterniflora*. SET-MH and RTK survey data do not necessarily show that elevation changes may be driving this vegetation shift, as elevation changes at SET 1 are keeping pace with sea level and the platform is well above mean high water. At Broadkill, no clear trends were discernible from biomass sampling at either SET. More data will be necessary to infer current cause and effect relationships between vegetation and elevation, as sea levels rise.

These vegetation relationships are more complicated at Christina, which demonstrated large inherent variation in data collected. More data will likely be necessary, such as those through permanent vegetation plots, biomass, and RTK-vegetation surveys, to infer which characteristics of the vegetation community are most intimately involved with cause-effect relationships between geomorphological changes and flora. Despite the inherent variability of vegetation at Christina, 2016 data appeared to be comparably higher than the preceding two years of sample collection. For exploratory purposes, above ground biomass was compared with variation in spring cloud cover, precipitation, and sea level anomalies at Christina. Significant correlations suggest that parameters may contribute to summer productivity in freshwater tidal marshes. Although no driving factors can be statistically identified from this comparison, future investigations of these responses may be key to understanding vegetation variability. For instance, a decrease in biomass with increased cloud cover could indicate a sensitivity to meteorological related climatic changes. This sensitivity could be exacerbated in Christina due to the dominance of C_3 plants; C_3 photosynthetic activity typically

decreases comparatively more than C_4 plants, such as *S. alterniflora*, in reduced light conditions (Sage and McKown 2006). Sea level during this time frame decreased slightly, which could have had a positive effect on biomass (Kearney *et al*. 2011). The statistical analyses of these responses, however, are limited due to the small sample size (N=4 years) so more data will be necessary to assess these relationships robustly.

In a comparison with other MACWA SSIM stations (Raper *et al*. 2016), Christina has exceptionally high dissolved organic carbon (DOC) and nitrate-nitrate concentrations, which coupled with relatively high chlorophyll α concentrations, suggests eutrophication. The high mean DOC resulted mainly from high values in 2016 and 2012, which averaged 17.3 (SE 1.38; N=10) and 53 (SE 0.68; N=10), respectively, whereas values from 2010-11 and 2013-15 averaged 3.71 (SE 0.18; N=45). These DOC spikes could have been caused by many factors, including sampling time, so more data are necessary. Salinity in Christina reflected some degree of salt water mixing, comparable to slightly higher salinity regimes (*cf* Wong 1979, where <6 ppt alkalinity values were <1 $meq \cdot L^{-1}$ or 50 $mg \cdot L^{-1}$ and zero salinity freshwater alkalinity was extrapolated to 0.7 $meq \cdot L^{-1}$ or 35 $mg \cdot L^{-1}$).* Total suspended solids (20.3 $mg \cdot L^{-1}$) appear to on average meet the threshold of sediment supply necessary for the marsh platform to keep pace with sea level rise (20 $mg \cdot L^{-1}$; Fagherazzi *et al*. 2012).

Water quality monitoring for Broadkill began in late 2014, so fewer data are available (Table 8). Over the short time period of sampling, DOC concentrations in Broadkill were relatively high compared to other MACWA SSIM stations (Raper *et al*. 2016), but not as high as Christina, on average. Chlorophyll α concentrations were also similar to Christina, and relatively high compared to other SSIM stations. Dissolved nutrient concentrations (nitrogen, phosphorous) at Broadkill were comparable to other SSIM stations in the salt marsh. Mean alkalinity during the short sampling time period was not anomalous with the mean salinity (cf Wong 1979, 26 ppt extrapolated to ~85 $mg \cdot L^{-1}$; Broadkill averaged 95 $mg \cdot L^{-1}$). Total suspended solids at Broadkill, like other marshes in the lower Delaware Estuary, surpassed the 20 $mg \cdot L^{-1}$ threshold (Fagherazzi *et al*. 2012), being nearly two-fold greater at ~50 $mg \cdot L^{-1}$.

Lastly, by using the new multi-metric MARS index (Raposa *et al*. 2016), the overall vulnerability of these two marshes was assessed. The index allows for a comparison of the two marshes, despite vegetation, salinity, and geomorphic differences. The indices for Christina suggest that is it slightly more vulnerable to sea level rise than Broadkill. This index is also useful in comparing these two marshes to other marshes across the country. For instance, marshes within the Narragansett Bay in Rhode Island had MARS indices of 1 for risk, 1.7 for average score, and a 0.66 ratio. This suggests that the marshes studied in Delaware are not as vulnerable to current rates of local sea level rise than marshes in New England. This conclusion should be taken with caution, however, as the index is focused on geomorphological characteristics only, and does not account for other changing environmental conditions such as past and current anthropogenic disturbance, meteorological changes, disruptions in plant productivity, and storm impacts.

*$meq \cdot L^{-1}$ =(0.01998) $mg \cdot L^{-1}$ (USGS 2001)

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Appendix I. Random Edge Vegetation Data

Table 9. Random edge (RE; N=6) vegetation data for Broadkill as well as relevant salt marsh epi/infaunal data (specifically *Geukensia demissa*, or ribbed mussel, lip counts, and the presence/absence of crab burrows, or bioturbation). Mean stem heights are averaged across all species, standard errors in parentheses.

Year	Plot ID	Plant Dominance		Mean Stem Height of Plot	Count of Stems	#*Geukensia demissa*	Bioturbation
		Dominant Species	%Cover				
2014	RE1	*Spartina alterniflora*	5	47.96 (1.7)	25	0	Absent
	RE2	*Spartina alterniflora*	25	94.40 (10.5)	15	1	Absent
	RE3	*Spartina alterniflora*	7	91.47 (4.9)	17	0	Absent
	RE4	*Spartina alterniflora*	10	93.94 (10.9)	16	0	Absent
	RE5	*Spartina alterniflora*	30	45.76 (2.02)	25	2	Absent
	RE6	*Spartina alterniflora*	15	71.58 (8.73)	19	0	Absent
2015	RE1	*Spartina alterniflora*	40	143.36 (6.09)	25	12	Present
	RE2	*Spartina alterniflora*	25	111.47 (2.97)	19	3	Present
	RE3	*Spartina alterniflora*	10	56.33 (7.93)	15	7	Present
	RE4	*Spartina alterniflora*	14	142.48 (6.06)	25	31	Present
	RE5	*Spartina alterniflora*	11	158.32 (6.63)	19	0	Absent
	RE6	*Spartina alterniflora*	15	132.64 (6.45)	14	0	Absent
2016	RE1	*Spartina alterniflora*	35	91.33 (12.1)	21	1	Present
	RE2	*Spartina alterniflora*	20	82.85 (7.11)	13	0	Present
	RE3	*Spartina alterniflora*	15	67.33 (5.49)	18	5	Present
	RE4	*Spartina alterniflora*	25	116.40 (5.98)	10	6	Present
	RE5	*Spartina alterniflora*	35	98.25 (2.57)	16	5	Present
	RE6	*Spartina alterniflora*	30	97.25 (8.62)	12	0	Present

Table 10. Random edge (RE; N=6) vegetation data for Christina. No epi/infauna were observed. Mean stem heights are averaged across all species, standard errors in parentheses.

Year	Plot ID	Plant Dominance		Mean Blade Height	Count of Blades
		Dominant Species	%Cover		
2011	RE1	*Pontederia cordata*	80	138.1 (4.35)	25
	RE2	*Nuphar lutea*	60	127.38 (12.6)	16
	RE3	*Nuphar lutea*	40	116.44 (7.52)	25
	RE4	*Nuphar lutea*	85	113.7 (6.16)	23
	RE5	*Peltandra virginica*	40	152.9 (10.1)	25
	RE6	*Nuphar lutea*	1	110.7 (4.45)	16
2012	RE1	*Polygonum sp.*	25	76.56 (3.83)	25
	RE2	*Nuphar lutea*	15	66.2 (4.76)	18
	RE3	*Nuphar lutea*	100	80.89 (4.41)	18
	RE4	*Nuphar lutea*	20	119.5 (7.02)	13
	RE5	*Nuphar lutea*	100	51.57 (3.88)	21
	RE6	*Nuphar lutea*	100	87.00 (4.37)	38
2013	RE1	*Peltandra virginica*	65	108.24 (4.08)	25
	RE2	*Nuphar lutea*	85	114.43 (3.26)	14
	RE3	*Nuphar lutea*	24	126.9 (5.39)	17
	RE4	*Nuphar lutea*	80	136.3 (4.01)	16
	RE5	*Nuphar lutea*	57	110.9 (3.99)	20
	RE6	*Nuphar lutea*	30	117.0 (0)	1
2014	RE1	*Nuphar lutea*	35	82.82 (3.77)	17
	RE2	*Nuphar lutea*	50	85.67 (5.40)	15
	RE3	*Nuphar lutea*	35	90.43 (14.2)	7
	RE4	*Peltandra virginica*	40	80.80 (4.87)	25
	RE5	*Calamagrostis sp.*	50	107.3 (8.70)	26
	RE6	*Nuphar lutea*	25	76.00 (5.48)	7
2015	RE1	*Pontederia cordata*	10	53.35 (8.09)	20
	RE2	*Nuphar lutea*	75	111.1 (2.98)	9
	RE3	*Nuphar lutea*	40	143.8 (1.74)	6
	RE4	*Schoenoplectus fluviatilis*	5	50.55 (5.63)	22
	RE5	*Calamagrostis sp.*	50	84.68 (6.15)	25
	RE6	*Calamagrostis sp.*	30	67.68 (4.39)	25
2016	RE1	*Nuphar lutea*	45	76.13 (3.03)	8
	RE2	*Nuphar lutea*	50	95.59 (5.96)	17
	RE3	*Nuphar lutea*	50	90.20 (3.89)	15
	RE4	*Schoenoplectus fluviatilis*	17	46.20 (3.96)	25
	RE5	*Calamagrostis sp.*	80	100.2 (6.48)	25
	RE6	*Nuphar lutea*	80	118.2 (3.35)	12

Appendix II. Marsh Resiliency to Sea-level Rise (MARS) Value Ranges for Scoring

Table 11. Range values for assigning MARS scores for each metric.

Metric	Scoring
Percent of marsh below MHW	>80% = 1 > 60% = 2 >40% = 3 >20% = 4 ≤20% = 5
Percent of marsh in lowest third of elevation range	>80% = 1 >60% = 2 >40% = 3 >20% = 4 ≤20% = 5
Skewness	>1.5 = 1 >0.5 = 2 <0.5, >-0.5 = 3 <-0.5 = 4 <-1.5 = 5
Elevation change rate ($mm \cdot yr^{-1}$)	≤2 = 1 >2 = 2 >3 = 3 >4 = 4 >5 = 5
Short-term accretion rate ($mm \cdot yr^{-1}$)	≤2 = 1 >2 = 2 >3 = 3 >4 = 4 >5 = 5

Metric	Scoring
Long-term accretion rate ($mm \cdot yr^{-1}$)	≤2 = 1 >2 = 2 >3 = 3 >4 = 4 >5 = 5
Turbidity (NTU) or Total Suspended Solids ($mg \cdot L^{-1}$)	≤10 = 1 >10 = 2 >20 = 3 >30 = 4 >40 = 5
Tide range (m)	≤0.6 =1 >0.6 = 2 >1.2 = 3 >1.8 = 4 >2.4 = 5
Long-term rate of SLR ($mm \cdot yr^{-1}$)	>3.4 = 1 >2.6 = 2 >1.8 = 3 >1 = 4 ≤1 = 5
Short-term interannual variation in water levels (mm)	>25 = 1 >15 = 2 >5 = 3 <5, >-5 = 4 <-5 = 5