Synthesizing NERR Sentinel Site Data to Improve Coastal Wetland Management Across New England
Data Report

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We dedicate this report to the memory of Dr. Michele Dionne, a tireless researcher and an early proponent of Sentinel Site monitoring.

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Abstract

Saltmarsh monitoring data collected from the four New England National Estuarine Research Reserves (NERRs) from 2010 to 2017 were combined to form one homogeneous database. These data were collected as part of the Sentinel Site Program, which is a component of the NERRs System Wide Monitoring Program (SWMP), designed to help manage local and regional salt marshes. The goal for this particular project was to synthesize the Sentinel Site data from salt marshes and identify significant changes over time in plant species abundance and marsh surface elevation as distinct from natural annual variation and provide products to help guide syntheses in different regions. As primary stakeholders, Reserve staff wanted to know if there were changes in their salt marshes and if such changes were reflected in the larger geography of New England. Staff from other state and federal agencies as well as non-governmental organizations were also interested in local and regional changes as well as learning what were the best methods for detecting environmental change that they could include in their monitoring programs.

Despite the use of a common protocol, many monitoring differences were identified among the Reserves. For example, relative abundance of plants by species was assessed using one of two common techniques: point intercept and ocular cover, so a correction factor was devised to make abundance values across Reserves comparable. Those differences that could not be rectified (e.g., plant height) were dropped from the regional analysis, but kept in the individual Reserve and regional datasets. In this way, each Reserve can confidently analyze their common and Reserve-specific data to generate and share information with local collaborators to support improved marsh management with changing climate.

Three tiers of increasing complexity (graphical, univariate statistics, and multivariate statistics) were used to analyze vegetation changes in eight marshes spread across four Reserves from Rhode Island to Maine. In all cases, significant trends were found that suggested marshes were becoming wetter, with low marsh losing plant cover and high marsh looking more like low marsh over time. Marshes in southern New England, Rhode Island and the southern shore of Cape Cod, had the most dramatic vegetation changes, co-occurring with relatively small tidal ranges. The marshes examined in Maine and New Hampshire have larger tides and showed less, but still significant changes. Both these results reflect the vulnerability of salt marshes to sea level rise in microtidal (more vulnerable) and mesotidal (less vulnerable) estuaries in a general sense. Inundation modeling examined temporal shifts in plant abundance from early to recent surveys with respect to tidal inundation and showed that flood-sensitive species were declining in the most frequently flooded plots. Taken together, inundation modeling and vegetation analyses show that *S. patens* and other flood sensitive species are being replaced by *S. alterniflora* as it migrates into higher elevation areas and suggest that inundation due to sea level rise is a key driver in vegetation changes.

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Introduction

Values of tidal marshes have become well-known over the past fifty years, from being considered wastelands to the recognition they possess a rich suite of ecosystem services that include habitat provisioning, storm protection and carbon sequestration (Costanza et al. 1987, Barbier et al. 2011). A small suite of perennial grasses and other plants have evolved to live in salt marshes. Despite their adaptations to extrude salts and ensure sufficient oxygen penetration to their tissues, flooding by seawater is stressful for halophyte plants. Accelerated rates of sea level rise coupled with subsidence has led to substantial marsh loss as seen in deltaic systems such as coastal Louisiana (Reed 1990), but less dramatic increases in relative sea level coupled with human actions (transportation corridors, dredging, inlet stabilization) can also result in dramatic ecological changes and significant marsh loss (Chesapeake Bay in Ward et al. 1998, Jamaica Bay in Hartig et al. 2002). In New England, Warren and Niering (1993) attributed the advance of low marsh plants into the high marsh to sea level rise at a salt marsh complex on eastern Long Island Sound. Since then, many researchers have found salt marsh responses to increased tidal flooding associated with climate change (Donnelly and Bertness 2002, Smith 2009, Raposa et al. 2016b, Watson et al. 2016).

In order to protect, conserve and restore tidal marshes state and federal agencies have supported monitoring and research to understand and manage these important estuarine systems. The National Estuarine Research Reserves (NERRs) were established to increase understanding and improve management of the Nation's estuaries through research, education and outreach. Many of the 29 NERRs established biomonitoring sites in tidal marshes in 2010 and 2011 with common protocols (Moore 2013) to identify and track changes in salt marshes at each Reserve and serve as 'Sentinel Sites' that could alert managers to local and regional changes. The Sentinel Sites Program was designed to identify changes in long-term trends, such as sea level rise (SLR), and an important aspect of the design and future analysis was to be able to identify and account for year-to-year variability. Our project combined seven or more years of monitoring data (plant communities, marsh surface elevation, local water levels, salinity, etc.) for the four New England Reserves (Figure 1) and synthesized the results. The New England Reserves span two biogeographic provinces, Acadian and Virginian, that correspond with different tidal ranges (mesotidal in the Acadian, microtidal in Virginian). Thus, we were able to examine the effect of tide range on marsh changes over time by comparing change at two Reserves that have small tide ranges with two that have larger tides.

In the present study, we also sought to examine the flood-frequency distribution of salt marsh vegetation in the Sentinel Site Program's monitoring plots of the four New England Reserves. Although vegetation abundance and elevation distributions with respect to marsh hypsometry likely differ among these marshes, the dominant plant species are similar. Where sufficient data were available (three Reserves: ME, MA, RI), we tied the plot elevations with local tidal data to assess flooding duration in relationship to vegetation or bare ground cover. These Reserves also had two different elevation surveys of their sentinel site plots, thus allowing us to conduct a change analysis of flooding duration and cover type.

An important component of the project was to provide each Reserve with their data in a common format following Quality Assurance/Quality Control (QA/QC) that is suitable for data reduction and statistical analyses. This empowers Reserve staff to analyze their data and collaborate with other Reserves to develop and answer questions of the dataset. To promote use, we highlighted three approaches to examining the data: graphic visualization without statistics, univariate parametric models with statistical results and multivariate analysis using PRIMER; other approaches are encouraged, such as the use of R scripts. Data quality is important, and we found a variety of differences among protocols that were measuring the same metric. We have identified inconsistencies and conflicting measures and shared them here, with the goal that protocols can be amended and unified in the future. Following data reformatting and corrections, most of the vegetation and surface elevation data for each Reserve were standardized across the four Reserves, with identical formatting, species names, species abundance metrics, and initial zone (habitat) designations. Some components could not be combined across Reserves due to methodological differences, such as plant height or algae cover, and these were included in each Reserve-specific data set so that the common elements could be analyzed along with the unique elements for each Reserve.

Figure 1. Location of the four National Estuarine Research Reserves in New England.

Methods and Approach

Marshes and Reserves:

The study marshes of Narragansett Bay NERR are located on Prudence Island. Three marsh areas shown in Figure 2 are regularly monitored: Nag is a back-barrier marsh on the western mid-section of the Island and Coggeshall Marsh is at the north end, sheltered behind and around peninsulas and islands. Coggeshall has two monitoring sites: a restoration site and a reference marsh area, but we examined only data from the reference site to avoid confounding sea level rise and restoration actions. Tides here range from about 0.8 m (2.6 feet) during neap and 1.8 m (5.9 feet) during spring tides.

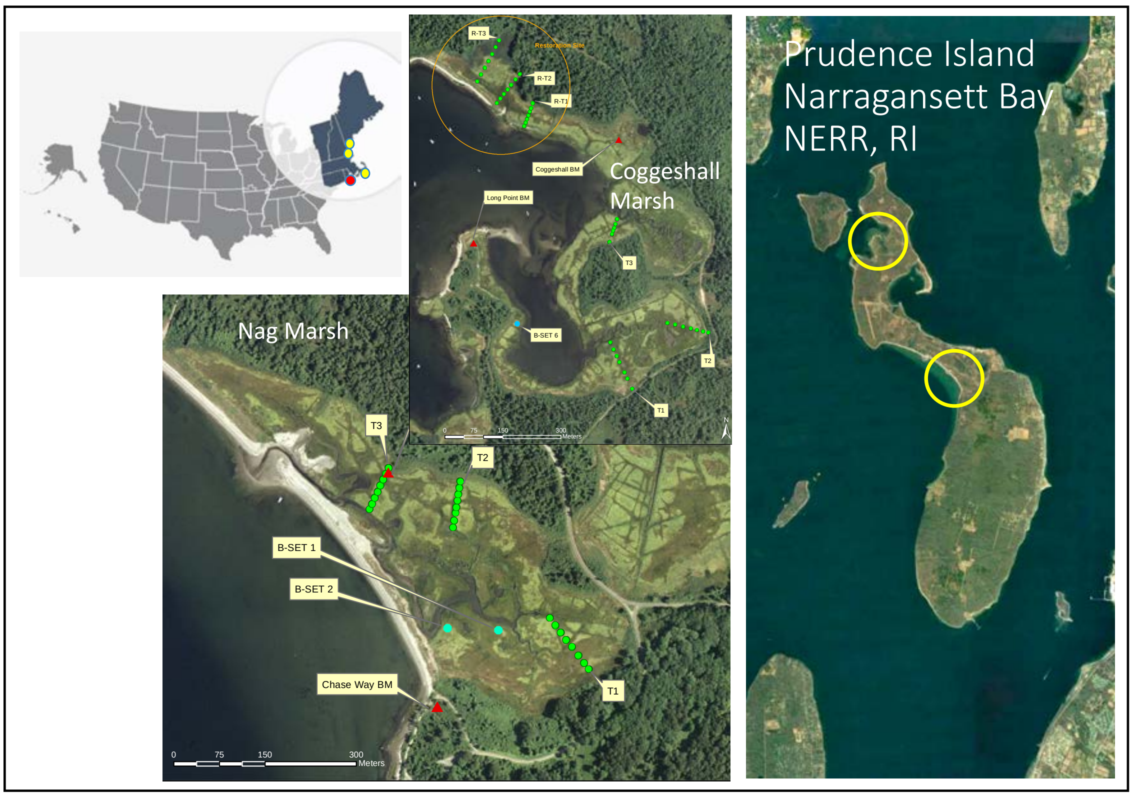

Figure 2. Narragansett Bay NERR on Prudence Island showing two biomonitoring sites.

Waquoit Bay NERR in Massachusetts lies on the southern shore of upper Cape Cod. Three salt marsh areas are regularly monitored that lie behind a barrier beach system (South Cape Beach) as shown in Figure 3. Only Section 1 and Section 2 were included in the analyses; Section 3 has recently restored hydrology following a culvert upgrade and Section 4 is an oligohaline marsh. Section 1 grades into dunes of the barrier beach and Section 2 ends in forested shoreline. The tide range here is small, about 0.5 m (1.6 feet) during neap and 1.0 m (3.2 feet) during spring tides.

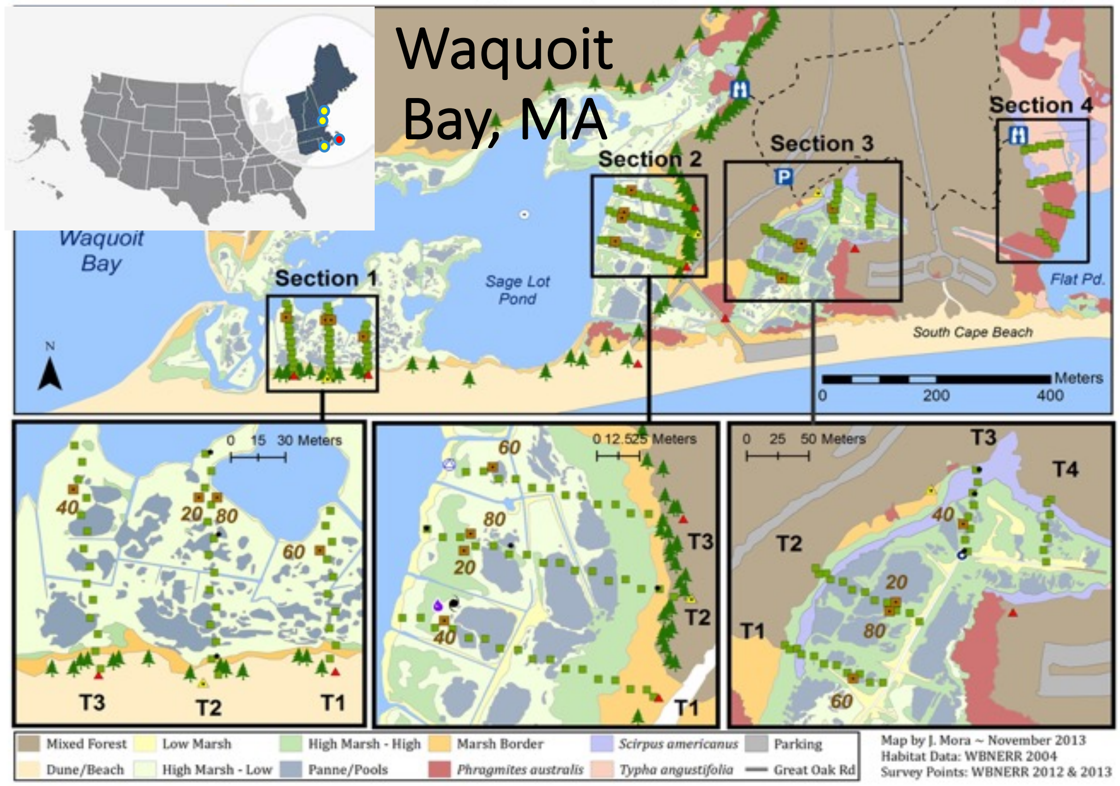

Figure 3. Waquoit Bay NERR on the south shore of Cape Cod showing biomonitoring sites.

Great Bay NERR in New Hampshire lies in the Acadian Province of the Gulf of Maine. It has three marsh monitoring sites. The largest is a bay-front marsh on the south shore of Great Bay, called Sandy Point Marsh, rises above the mudflat as a steep, eroding scarp and extends across a broad plain grading into freshwater forested wetland. The other two sites are small riverine marshes with central tidal creeks and steeply sloping uplands: Great Bay Farms Marsh and Bunker Creek Marsh (Figure 4). The tide range here is moderate, about 1.5 m (4.8 feet) during neap tides and 3.0 m (9.8 feet) during spring tides.

Wells NERR in southern Maine encompasses two estuaries with barrier beach systems. The marsh monitoring site is composed of eight transects extending eastward from the landward edge of the Webhannet Marsh, chosen to reflect developed and undeveloped shoreline conditions (Figure 5). Unlike at other Reserves, transects here do not extend fully from the upland to the main tidal inlet. Instead, transects extend seaward from the upland approximately 200 m, ending at a tidal creek. The tide range here is the largest of the four Reserves, about 2.0 m (6.5 feet) during neap and 3.9 m (12.8 feet) during spring tides.

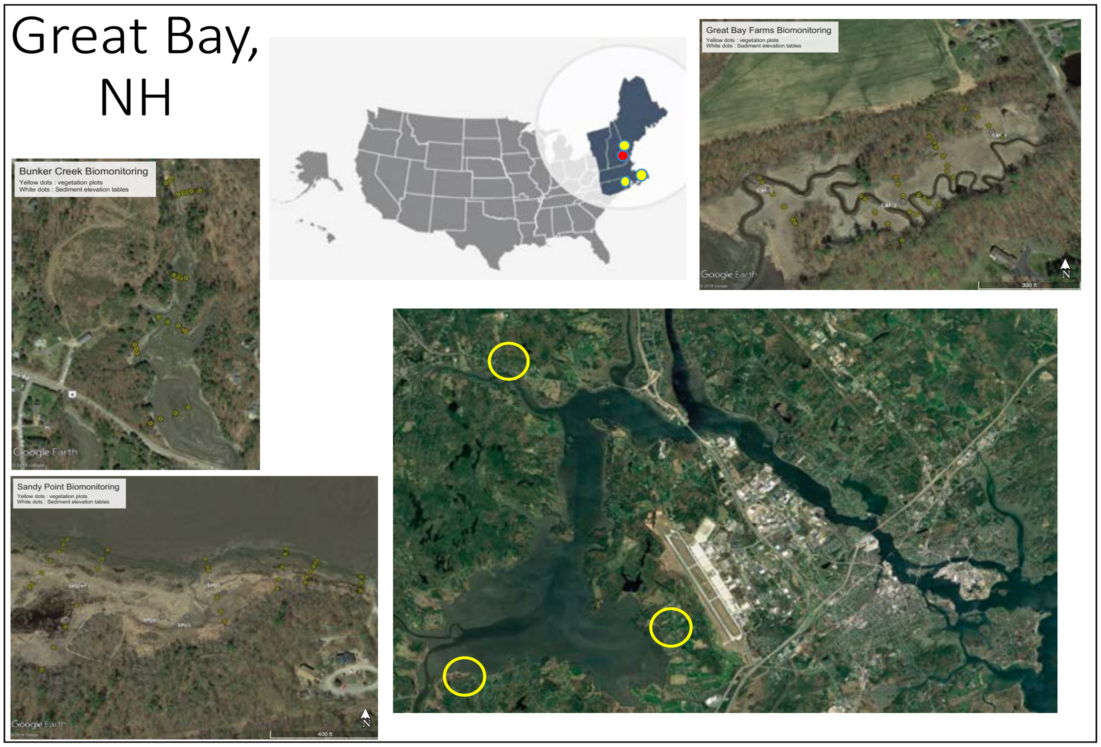

Figure 4. Great Bay NERR showing three biomonitoring sites.

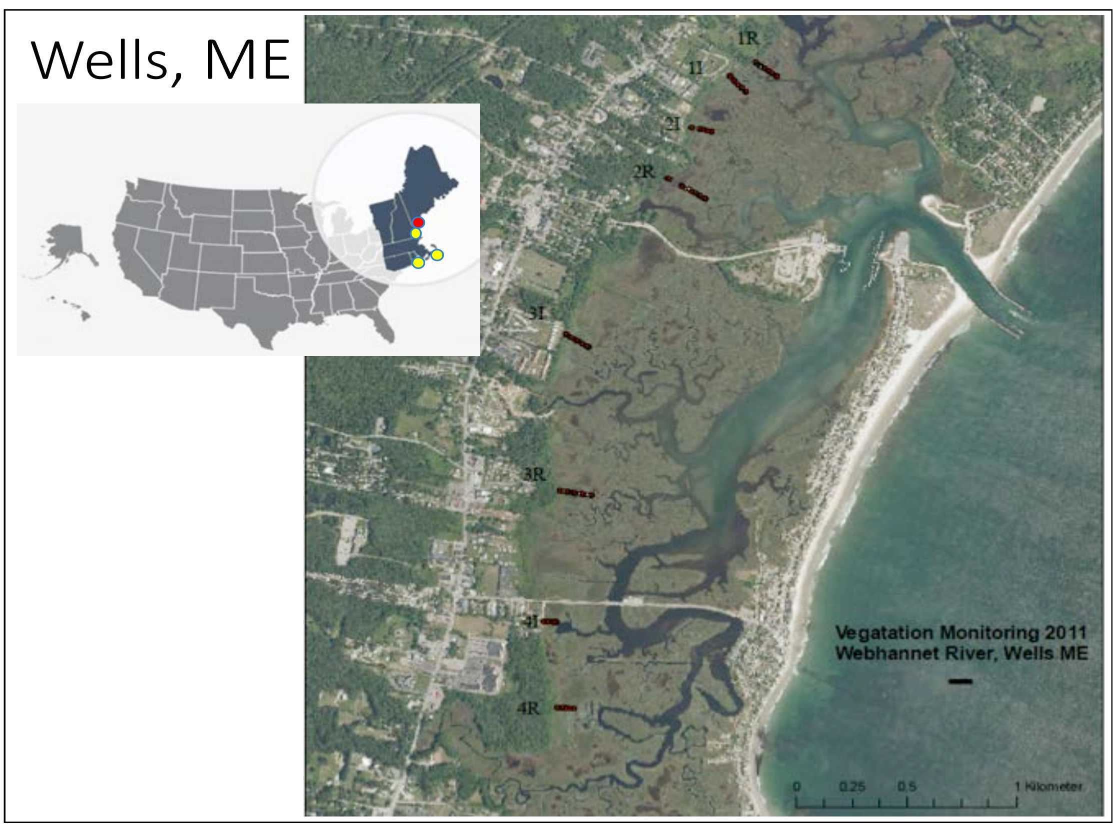

Figure 5. Wells NERR showing one biomonitoring site of eight transects in Webhannet Marsh.

Reformatting Data and Statistical Approaches:
Data were obtained from individual Reserves in formats prescribed by the Central Data Management Office (CDMO) or preliminary formats as input by the different Reserves. Reformatting and standardization included transposing the data so each observation (sample plot) used only one row in the dataset, with each cover type (living and non-living) using a separate column. Species names were examined for discrepancies and updated where appropriate. In cases where species within a genus were not distinguished, even for one Reserve, only the genus was used (e.g., *Salicornia*). For more details describing method reconciliation, data reformatting, standardization, and other issues addressed in combining datasets, consult our "Guide for Synthesizing NERRs Marsh Monitoring Data" (Burdick et al. 2020; http://www.nerrssciencecollaborative.org/project/Burdick18).

Plant cover is one of the most important components of marsh monitoring and data analysis. In New England, two common plant cover data collection methodologies were used: Ocular Cover and Point Intercept. Ocular Cover (OC) records visual estimates of cover, whereas Point Intercept (PI) records presence/absence by point 'hits'. For New England Reserve data, OC estimated to the nearest percent (non-binned) for each species or cover group with the total set to 100%, whereas PI recorded each species that was 'hit' with the total not set to 100%. Through statistical analysis, we found these different methodologies can have significant effects on data analysis and interpretation. In a separate but related project, our team developed a simple, novel and more accurate approach to integrate the two most common cover methods (Figure 6). We transformed PI data to be more compatible with OC data using a series of linear regressions across groups of cover with similar morphologies using data from over 100 plots monitored with both PI and OC. This method, called Regressions Across Morphological Archetypes (RAMA), is detailed in our other guide titled "*A Guide to Integrate Plant Cover Data from Two Different Methods: Point Intercept and Ocular Cover*" (Peter et al. 2020; http://www.nerrssciencecollaborative.org/project/Burdick18).

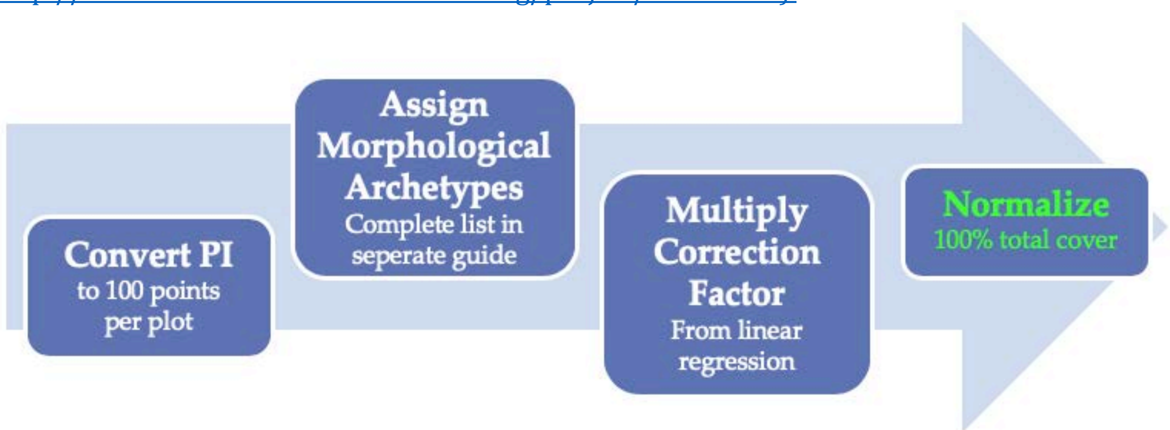

Figure 6. The four-step approach to integrate Point-intercept with Ocular cover data using regressions across morphological archetypes.

Once data were formatted, underwent QA/QC, and were limited to a standardized set of metrics they were combined for all years and Reserves. First, simple pie charts were constructed for visualization of plant abundance and change over time in each habitat of each marsh from each Reserve. Data were summarized into categories for ease of visual interpretation. The graphic analysis showed clear trends within and across Reserves and provided the Reserves with a template for graphic analysis of additional data over time and vegetation change at their other marshes.

Statistical analyses focused on several important questions for plant abundance and marsh surface elevation: Are New England salt marshes changing over time? What is the year-to-year variability? Do changes over time represent a significant trend? Are responses in the two southern Reserves (small tide ranges) different than that of the two northern Reserves (large tide ranges)? Most of these questions were addressed using simple univariate analyses of plant cover and derived metrics (e.g., *Spartina alterniflora* to *S. patens* ratio, species richness per plot) using general linear models with fixed effects. Multivariate analyses examined differences between Reserves, regions with respect to changes in the plant community over time. In addition, plot elevation and tidal records were used with plant abundance to produce inundation models showing the distribution of species relative to flooding regime in the marshes.

Graphic Analysis Using Pie-Chart Visualizations:
Plant composition and changes in marsh vegetation were visualized by the creation of pie charts, which were created for each marsh within each Reserve using plant cover estimates for each year of available data between 2010 and 2017 as well as for each marsh zone. Subdividing marshes by zone was found to enhance the resolution of plant communities for visualizing change over time as sea-level-rise can have different responses in different marsh zones. For instance, increased inundation can lead to decreases in cover of *S. alterniflora* in the low marsh but can increase its cover in the high marsh (Warren and Niering 1993, Smith 2009, Watson et al. 2017). For all four New England Reserves, we binned monitoring plots into three distinct marsh zones: Low Marsh, High Marsh, and Upland Edge (Nixon 1982; for details see our "Guide": Burdick et al. 2020). And for Great Bay, a fourth Transition Zone, which included two monitoring plots located on the original boundary of the low and high marsh for each transect, was graphed.

Plant cover and abiotic covers (e.g., bare ground, dead) were individually highlighted or summarized into categories for ease of visual interpretation. Individual dominant species such as the *S. alterniflora* and *S. patens* were highlighted. Categories were determined by ecological similarities: Great Bay (GRB), Narragansett Bay (NAR), and Wells (WEL) included (1) Bare and Dead, (2) Wrack, (3) *S. alterniflora*, (4) *S. patens*, (5) Halophytic

Grasses and Shrubs, (6) Halophytic forbs, (6) Brackish, (7) Fresh (freshwater upland species), and Invasive, while Waquoit Bay (WQB) included: (1) Bare and Algae, (2) Dead, (3) Wrack, (4) *S. alterniflora*, (5) *D. spicata, J. gerardii, S. patens,* (6) Halophytic forbs, (7) *I. Fructescens*, *B. halimifolia*, (8) Brackish, and (9) Other. Plant cover and abiotic categories were decided upon by each Reserve to best summarize their specific plant communities.

Univariate Analyses:
Univariate analyses, where one dependent variable is examined at a time, were conducted using JMP™ software. A small group of variables, selected based on dominance and presence, included the two most dominant species (*Spartina alterniflora*, *Spartina patens*), the ratio of them (SA:SP), grouped species (all halophytes, forbs, the high marsh perennial grasses *D. spicata* + *J. gerardii* + *S. patens*), grouped non-living cover (bare + dead + wrack) and species richness per plot. The SA:SP ratio is:

$$SA{:}SP = \frac{S.alterniflora}{S.alterniflora + S.patens}$$

Analyses were run for the entire dataset, northern vs. southern Reserves as well as individual Reserves (Reserves had 1-3 marshes, and these are termed 'sites'). Replicate plots within zones were averaged for each marsh because interannual variability was generally high within specific plots. The best explanatory model that accounted for most of the variation in cover of important species and cover types (except for forbs) included marsh site, plot habitat (zone), and year as a covariable, with two-way interactions. Residuals were examined, and some variables were transformed to ensure even variance with changes in abundance and normal distribution.

Multivariate Methods:
Marsh vegetation communities were further analyzed using non-metric multivariate tests using PRIMER 6 version 6.1.9 (Clarke and Gorley, 2001), which included non-metric multi-dimensional scaling (MDS), analysis of similarity (ANOSIM), and contributions to similarity analysis (SIMPER). These tests were chosen for their flexibility to handle non-parametric datasets as well as their ability to account for multiple community characteristics (e.g., composition, abundance, diversity). Plant community data (in the form of percent cover) were standardized using either a square-root or 4th root transformations, when appropriate, then analyzed as a Bray-Curtis similarity matrix. For each comparison, MDS were run using 100 iterations and ANOSIM were run using 999 permutations. Stress, shown on the MDS plots, which indicate how well the Bray-Curtis similarity matrix matches up with the dimensional relationships among samples in the ordination. PRIMER's guidance on stress values is as follows:

$\leq$0.05	Excellent	>0.05 x <0.1	Great
>0.1 x <0.2	Good	>0.2	Poor

Our multivariate approach was designed to test our main hypothesis: Are New England salt marshes changing over time? As such, time was our primary treatment. To address this main hypothesis as well as handle the large volume of data and potential tests, we utilized a two-tiered approach. First, a series of one-factor ANOSIMs were conducted to test for significant differences in plant communities from the first year to last year of available data for each marsh (n=8), Reserve (n=4) and sub-regions (n=1) and New England as a whole (n = 1) as well as across distinct marsh zones (low marsh, transition when noted, high marsh, upland edge). A total of 60 comparisons were run. In contrast, the same statistical approach with the addition of all potential year combinations would require over 1600 comparisons. Second, when significance ($p<0.05$) or a general trend ($p<0.20$) was identified, this triggered further investigation using MDS to visualize community differences between plots and SIMPER to determine the species contributing most to any differences detected between groups of sample. Complete ANOSIM and SIMPER results as well as MDS graphics are associated with this second tier of investigation. Note, for marshes in Great Bay and Coggeshall marsh in Narragansett Bay, the first vs last time period was 2010 to 2017. For Nag marsh at Narragansett Bay, we examined 2010 to 2015 due to concerns of data quality in 2016-17. The time period analyzed for Waquoit Bay marshes was 2011 to 2017 and for Wells marsh, 2011 to 2016.

Inundation Modeling:
Inundation modeling was performed to examine the flooding duration of salt marsh vegetation in the Sentinel Site monitoring plots of three New England Reserves which span two biogeographic provinces (Acadian and Virginian) corresponding to mesotidal (ME) and microtidal (MA and RI) tidal regimes. Although vegetation abundance and distribution differ among these marshes, the dominant plant species are similar. Where sufficient data were available, plot elevations (NADV88) were combined with local tidal data to assess flooding duration in relationship to vegetation or bare ground cover. Due to time constraints, interpretation is based on graphic visualizations. The three Reserves that had sufficient data to conduct the inundation analyses (ME, MA, RI) also had two different elevation surveys of their vegetation plots, thus allowing us to conduct a visual analysis of change using early (2010-2013) and recent (2016-2018) survey periods of flooding duration and cover type.

The inundation analysis was run for each Reserve for two time periods categorized by: “early” (2010-2013) and “recent” (2016-2018). The years vary depending on the Reserve and when the appropriate data (particularly elevation measurements) were available (Table 1). Data required to run the analysis included water level measurements, elevation measurements, and vegetation measurements (percent cover using point intercept for RI and ME, ocular estimates for MA) for each marsh site. Depending on the Reserve, the water levels were either measured directly in the marsh or downloaded from the nearest NOAA

CO-OPS tide gauge (Table 1). All of the elevation and vegetation data used for the analysis were taken from the New England Reserve regional database compiled for this project (2010-2017). The only exception was the data used for the recent Waquoit Bay analysis for 2018 which was supplied by Waquoit Bay staff. Each Reserve's inundation calculations were first analyzed separately and then the Reserve-specific results were compiled onto one figure for each vegetation/cover category.

For each time period (early and recent), percent flooding for each Reserve marsh site was calculated using a macro developed by Jim Lynch (National Park Service). To run the macro, water levels measured every 6 minutes over a one-year period were entered into a spreadsheet. Some data gaps exist for water level monitoring during winter (e.g., ice necessitated removal of the Waquoit float arm gauge). One marsh surface elevation, based on an average of 4-5 elevation observations within a plot, was entered for each plot. The macro determined how many times over the year the specific elevation was inundated and calculated a percent time flooded. This process was repeated for every plot in the marsh. After the percent flooding was calculated for each plot in each marsh, it was compiled into a database and compared to the percent cover of vegetation for each Reserve marsh site for each time period. The analysis was conducted for the following categories/plant communities: Bare + Dead +Algae (note: only Waquoit Bay had dead and algae categories), *S. alterniflora, S. patens, D. spicata, J. gerardii*, and the flood sensitive species grouped: total cover of *S. patens* + *D. spicata* + *J. gerardii*. Narragansett Bay and Wells both use point intercept methods for vegetation sampling and thus have percent cover values that sometimes exceed 100%.

Table 1 lists the four marsh sites (two for Waquoit Bay) that were included in this inundation analysis. Due to data availability constraints, not all of the Reserve Sentinel Site marshes were included in the analysis. Sites excluded from the analysis include: Nag marsh (Narragansett Bay) and section 3 marsh (Waquoit Bay), both of which did not have the appropriate water level data available; and Great Bay, which did not have elevation data available for the time periods included in the analysis.

SET and MH methods:
Installation and measurements of surface elevation tables (SETs) have changed over the past 25 years with some Reserves having original (Boumans and Day 1993) and others the R-SET (Cahoon et al. 2002). Essentially, the SET sits upon a benchmark driven to the point of refusal and 36 pins are dropped to the marsh surface to measure changes in the marsh elevation. In addition, a marker horizon of feldspar can be applied to 2 to 4 specific locations relative to the benchmark to track the deposition of sediments on the marsh surface (e.g., accretion). A national protocol for SET and marker horizon establishment and

measurements has been established (Lynch et al. 2015) and NERRs follow these protocols.

Table 1. Parameters collected for tidal inundation. Elevation and water level data were used to calculate percent flooding.

Reserve	Site	Elevation (NAVD88, m)	Water Level Data (NAVD88, m)
Narragansett Bay	Coggeshall Marsh	Collected by RTK in 2010 and 2016	6 minute data downloaded from Newport, RI tide gauge (station ID 8452660) for 2010 and 2016
Waquoit Bay	Sage Lot Marsh (section 1 & 2)	Collected by RTK in 2012/2013 and by Laser level in 2018	6 minute data collected in Sage Lot Marsh using a float arm gauge for 2013 and 2018
Wells	WB Marsh	Collected by RTK in 2011 and 2016	6 minute data downloaded from Wells, ME tide gauge (station ID 8419317) for 2011 and 2016

Results and Discussion

We used three complementary approaches for detecting vegetation changes, graphic visualization of plant cover using pie charts, univariate analyses using ANCOVA with JMP™, and multivariate community analysis using ANOSIM and other techniques with PRIMER™. A fourth analysis, the proportion of plant cover plotted against flooding frequency over two time periods in each Reserve was conducted using an Inundation Model to determine if species were shifting in response to sea level rise.

Graphic Vegetation Analysis Using Pie-Chart Visualizations:

Pie chart visualizations were easily generated, interpreted and particularly effective at illustrating change over time and useful for drawing similarities and comparisons between marshes within and among Reserves. For less abundant species, similar plants were combined into groups (e.g., halophytic forbs, brackish species) to help show general trends over time. Overall, marshes across New England have changed between 2010 and 2017 toward communities indicative of wetter environments. Low marsh areas displayed a loss of live cover and increase in bare sediments, while high marsh areas showed an increase in *S. alterniflora* and a decrease in one of the high marsh dominant plants, *S. patens* (Figure 7). Overall, upland edge plots also displayed transition towards wetter, more tidally influenced systems with greater brackish species cover. See Table 2 for a summary of trends for each Reserve and Appendix A for individual pie-charts for each marsh and Reserve.

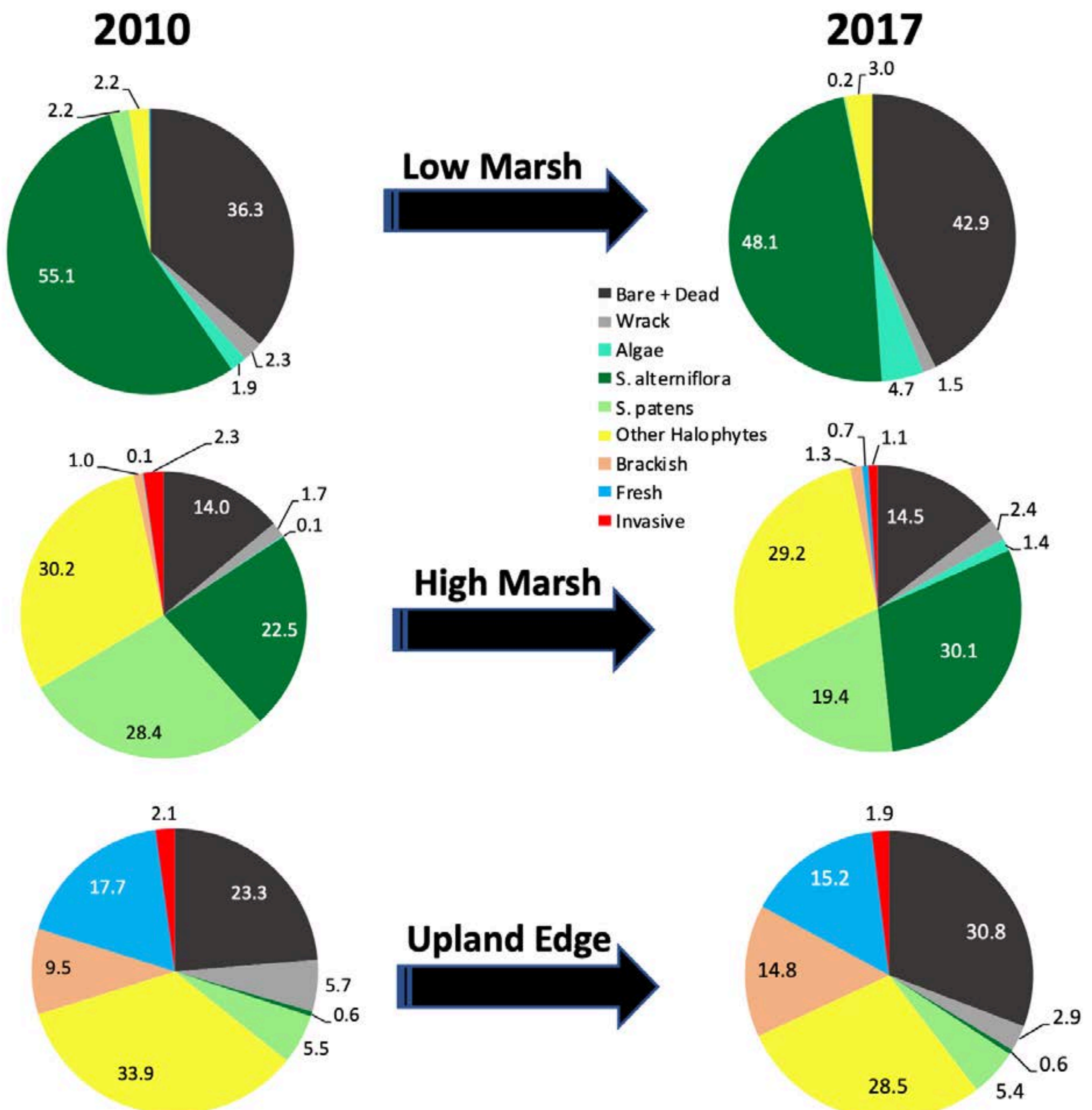

Figure 7. Proportion of coverage for each marsh zone for all four Reserves averaged, showing overall changes from 2010 to 2017. Early data for Waquoit Bay were collected in 2011.

Across Reserves, we find repeating patterns as well as unique patterns moving from south to north over the monitoring period. Vegetation changes are illustrated for two marshes on Prudence Island in Narragansett Bay, where inundation appears to be impacting plant communities. In low marsh zones, *S. alterniflora* is being replaced by unvegetated bare cover (-14% and +15%, respectively) at Coggeshall marsh and *S. patens* is replaced by *S. alterniflora* at Nag marsh (-7% and +8%, respectively). Similarly, in high marsh zones, cover of *S. patens* is reduced by nearly three-fold (33% to 13%) at Coggeshall and *S. patens* is replaced by *S. alterniflora* (-11% and +15%, respectively) at Nag marsh.

To the east, we report changes in two marsh areas of Sage Lot Pond at Waquoit Bay NERR. At Waquoit Bay's marshes (Section 1 - dune at upper edge and Section 2 - forest at upper edge), we find a repeating theme from 2011 to 2017, with Section 1 low marsh showing bare ground replacing *S. alterniflora* cover (+ 11% and -17%, respectively). In the high marsh, *S. alterniflora* increased in cover (+8%) in Section 2 and high marsh grasses *J. gerardii, D. spicata,* and *S. patens* decreased in cover in both marshes. Upland zones of Waquoit's Section 1 marsh showed a 15% increase in brackish cover from 2013 to 2017.

At Great Bay, shifts in communities are evident in marsh zones from 2010 to 2017, with the largest monitored marsh in NH (Sandy Point) showing *S. alterniflora* being replaced by unvegetated bare cover in the low marsh (-20% and +11%, respectively), *S. alterniflora* replacing *S. patens* in the high marsh (+5% and -10%, respectively) and an increase in brackish and bare cover in the upland edge (+11% and +22%, respectively). Slight increases in presence of *S. alterniflora* were also seen in the high marshes at Great Bay's Bunker Creek and Great Bay Farms (0% to 1.7% and 2.7% to 6.5%, respectively). The upland edge zone at Bunker Creek marsh also increased in bare and dead cover by 26% and decreased in freshwater species by 17%. However, the largest signal was found in the transition plots, where *S. alterniflora* increased from 34% to 67% at Sandy Point marsh. This trend was reinforced in Great Bay's Bunker Creek and Great Bay Farms transition plots with *S. alterniflora* replacing *S. patens* (+21% and -14%, respectively at Bunker Creek and +20% and -11%, respectively at Great Bay Farms).

At Wells high marsh plots, there is large decrease in cover of *S. patens* of roughly half (41% in 2011 to 23% in 2017), with a corresponding increase in *S. alterniflora* (42% to 59%). Additionally, upland edge communities started off with <1% cover of halophytic forbs in 2011, but steadily increased to 24% in 2017.

Table 2. Marsh specific trends for each marsh and Reserve, examined by habitat type across the full monitoring time period. Note, only Great Bay monitors transition plots located at the boundary of the low and high marsh zones.

Reserve	Low Marsh	Transition	High Marsh	Upland
Narragansett Bay Coggeshall	- *S. alterniflora* + Bare and Dead	n/a	+ Bare and Dead - *S. patens* -Halophytic grasses and shrubs	+ Invasive species
Narragansett Bay Nag	+ *S. alterniflora* - *S. patens*	n/a	+ *S. alterniflora* - *S. patens*	+ *S. patens* - Halophytic grasses and shrubs
Waquoit Bay Section 1**- dune edge**	- S. alterniflora + Bare	n/a	- *J. gerardii, D. spicata* , and *S. patens*	+ Brackish species
Waquoit Bay Section 2 **- forest edge**	+ Bare	n/a	+ *S. alterniflora* - *J. gerardii, D. spicata* , and *S. patens*	+ Dead - *J. gerardii, D. spicata* , and *S. patens* + Halophytic forbs
Great Bay Sandy Point	- *S. alterniflora* + Algae + Bare and Dead	+ *S. alterniflora*	+ *S. alterniflora* - *S. patens* + Halophytic grasses and shrubs	+ Brackish species
Great Bay Bunker Creek	No change	+ *S. alterniflora* - *S. patens*	+ *S. alterniflora*	- Freshwater species + Bare and Dead
Great Bay Great Bay Farms	No change	+ *S. alterniflora* - *S. patens* -Halophytic forbs	+ *S. alterniflora* - Bare and Dead	No change
Wells Webhannet River	+ *S. alterniflora* - *S. patens* + Halophytic forbs	n/a	+ *S. alterniflora* - *S. patens*	+ Halophytic forbs

Univariate Analyses:

Statistical analyses of particular species, cover types and various combinations were performed on 1,539 observations across the four Reserves using ANCOVA, with Site and Marsh Zone as main effects and Year as the covariable. Overall, each Reserve and each marsh within Reserves were different, so the marsh site effect was large. Marsh zone (i.e., habitat type) was a critical main effect because plant abundance in different parts of the marsh vary. In addition, species within Zones behaved differently over time. For example, *S. alterniflora* decreased over time in the low marsh but increased in high marsh plots; this is shown as a significant Marsh Zone by Year interaction (Table 3; Figure 8).

Table 3. Model results for univariate ANCOVA for four Reserves combined showing *p* values for Site, Zone and Year and their interactions as well as the overall *F* statistic and proportion of variance explained, R^2. Dispi+Juger+Sppat = *Distichlis spicata*, *Juncus gerardii* and *Spartina patens* combined.

Dependent Variable	Transformation Data Excluded	n	Overall F	R2	SITE	MARSH ZONE	YEAR	Site X M Zone	Year X M Zone	Year X Site
Spartina alterniflora	LN*; 1 outlier removed	151	279	0.99	0.0001	0.0001	0.6529	0.0001	0.0005	0.1482
Spartina patens	none	151	119	0.97	0.0001	0.0001	0.0001	0.0001	0.0001	0.0120
SA : SP Ratio	ArcSin; upland edge plots	102	307	0.99	0.0001	0.0001	0.0001	0.0001	0.0001	0.0301
HM Grasses and Shrubs	SqRt	151	101	0.97	0.0001	0.0001	0.0280	0.0001	0.2422	0.0484
Dispi + Juger + Sppat	LN; low marsh plots	100	70	0.96	0.0001	0.0001	0.0092	0.0001	0.0037	0.0490
Forbs LN	LN	151	12.0	0.77	0.0001	0.0001	0.5268	0.0001	0.3146	0.0276
Species richness	LN	151	61	0.94	0.0001	0.0001	0.4979	0.0001	0.6989	0.1185
Non-Living	none	151	30	0.90	0.0001	0.0001	0.0001	0.0001	0.8095	0.0863
Bare Sediment	LN	151	14.3	0.80	0.0001	0.0001	0.0010	0.0001	0.3825	0.0067

*distribution of residuals non-normal

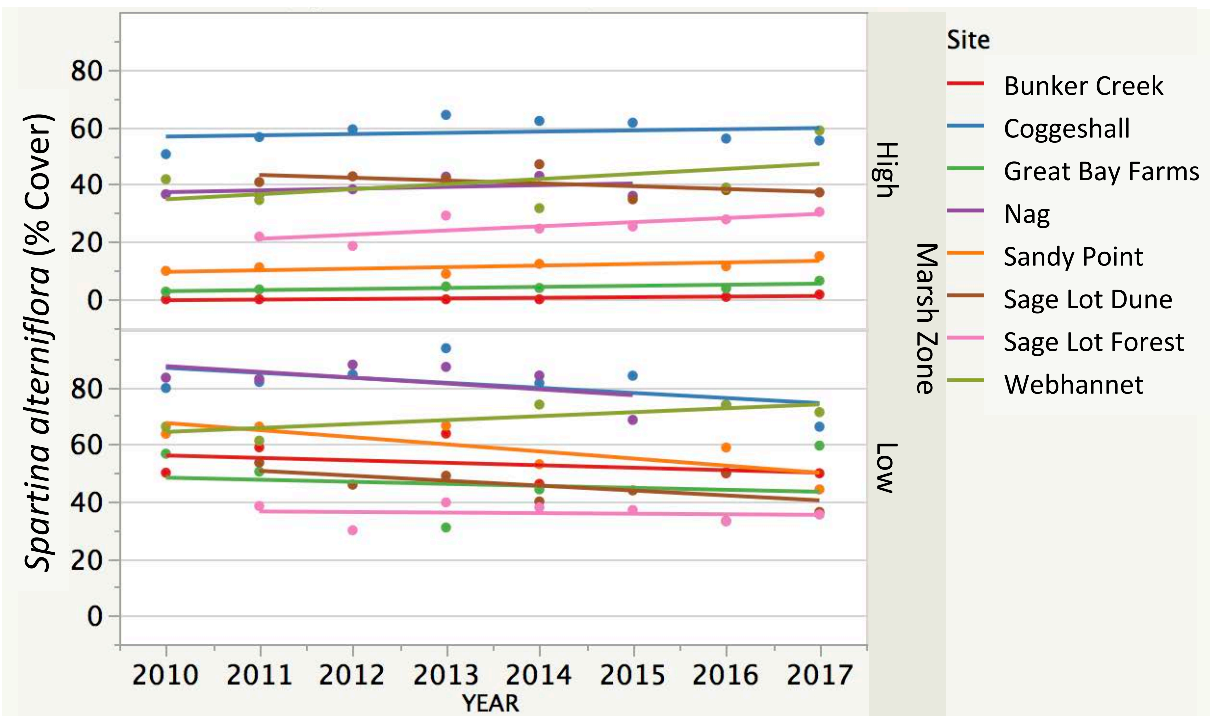

Figure 8. Changes in cover of *Spartina alterniflora* for low and high marsh zones in eight salt marshes of the four New England Reserves. Marshes in Waquoit Bay lie within Sage Lot Pond and include Dune edge marsh (Section 1) and Forested edge marsh (Section 2).

An important result showed that year-to-year variation in the cover of specific or total live marsh plants was not large enough in New England to prevent us from identifying long-term trends, likely associated with increases in sea level rise (Figure 8). Although our results only associate vegetation changes over time with sea level rise in a correlative way, they have met the national goal for establishment of the NERR sentinel sites (NERRS 2012).

Over all four New England Reserves combined, temporal trends in plant abundance indicate low marshes are becoming less vegetated, the low marsh dominant, *S. alterniflora*, is advancing into the high marsh, and typical high marsh species are becoming less abundant. These trends were found within individual Reserves as well. Detailed results for individual Reserves can be found in Appendix B. Previous work in Connecticut (Warren and Niering 1993), Rhode Island (Donnelly and Bertness 2001, Raposa et al. 2016b, 2017, Watson et al. 2017) and Massachusetts (Smith 2009, 2015) attribute similar trends over time to sea level rise. Using consistent methods, our results detail patterns in vegetation associated with accelerated sea level rise across Reserves in four New England states, strengthening the case for widespread impacts from climate change.

Regional analysis comparing marshes in the Acadian and Virginian provinces was performed by averaging cover types in the four southern and northern marshes. Because cover types among marshes varied considerably, the ability of the model to account for variation in the data was lower, with R^2 ranging from 0.31 to 0.88 (Table 4). Nevertheless, comparison of southern, microtidal Reserve marshes with northern, mesotidal Reserve marshes showed geographic and temporal effects, with more rapid declines of key species in the south: *S. alterniflora* in the low marsh and *S. patens* in the high marsh (Figure 9). The spring tide range at the two southern Reserves is 1.0 to 1.8 m and 3.0-3.9 m for the two northern Reserves, so the proportion of sea level rise over the eight-year monitoring period is relatively greater for the southern Reserves. This appears to be reflected in the greater vegetation changes observed in the southern Reserves. Vegetation changes in New England marshes were first reported in Connecticut (Warren and Niering 1993) and Rhode Island (Donnelly and Bertness 2001) before being reported in Gulf of Maine marshes (Smith 2009, this study).

The univariate analyses supported the overall trends shown in the pie chart visualizations, but also provided statistical support and valuable insights for change at all scales, including individual marshes, which are also supported by multivariate analyses. The univariate models were also able to provide details about changes in specific cover types (e.g., SA:SP ratio) and tease out details of specific marshes that could be valuable for management. Details may be found in Appendix B, but four examples of site-specific results follow. Nag Marsh in Rhode Island, which was higher in elevation than Coggeshall Marsh (Raposa et al. 2016b), was shown to have greater cover of high marsh grasses, especially *S. patens,* than Coggeshall Marsh (Figure B-1). However, both marshes showed clear declines of *S. patens* and the sum of high marsh grasses (Sp+Ds+Jg) in the high marsh. Both these marshes also showed declines of *S. alterniflora* in the low marsh (replaced by bare mud) as indicated by significant Year by Zone interaction terms. In Waquoit, the two marshes bordering Sage Lot Pond showed mixed results with temporal changes in *S. alterniflora* cover, but *S. patens* and Sp+Ds+Jg exhibited clear and significant declines over time in all zones of both marshes (Table B-2, Figure B-2). The loss of species typically found in the high marsh exhibited a strong temporal effect in Narraganset and Waquoit marshes, similar to patterns reported in 2017 by Watson and colleagues working in Rhode Island. In Great Bay marshes, where plots were established in the transition zone between low and high marsh, the advance of *S. alterniflora* over *S. patens* was made clear and accentuated with the SA:SP results (Figure B-3). The SA:SP ratio was the only independent variable with a significant year effect that showed this pattern in Wells, Maine (Table B-4, Figure B-4). Most importantly, the changes observed in southern New England marshes (Connecticut: Warren and Niering 1993; Rhode Island: Donnelly and Bertness 2001, Raposa et al. 2017, Watson et al. 2017b; Massachusetts: Smith 2009, 2015) are clearly seen and have statistical significance in northern New England.

Table 4. Model results for univariate ANCOVA comparing two southern and northern Reserves showing *p* values for Region, Zone and Year and their interactions as well as the overall *F* statistic and proportion of variance explained, R^2.

Dependent Variable	Transformation Data Excluded	n	Overall F	R2	REGION	MARSH ZONE	YEAR	Region X M Zone	Year X M Zone	Year X Region
Spartina alterniflora	upland edge plots	102	22.5	0.59	0.0001	0.0001	0.2351	0.0004	0.0905	0.1870
Spartina patens	LN	151	31.2	0.67	0.6962	0.0001	0.0077	0.1367	0.0968	0.0002
SA : SP Ratio	Ln of ArcSin*; upland edge plots	101	119	0.88	0.0001	0.0001	0.0001	0.0001	0.4318	0.2455
Forbs LN	LN	151	7.7	0.33	0.1752	0.0001	0.2324	0.3282	0.7517	0.0583
Species Richness	LN	151	48	0.75	0.3510	0.0001	0.6484	0.0918	0.8699	0.8949
Non-Living	ArcSin	151	7	0.31	0.0057	0.0001	0.0012	0.0036	0.8871	0.0022
*distribution of residuals non-normal										

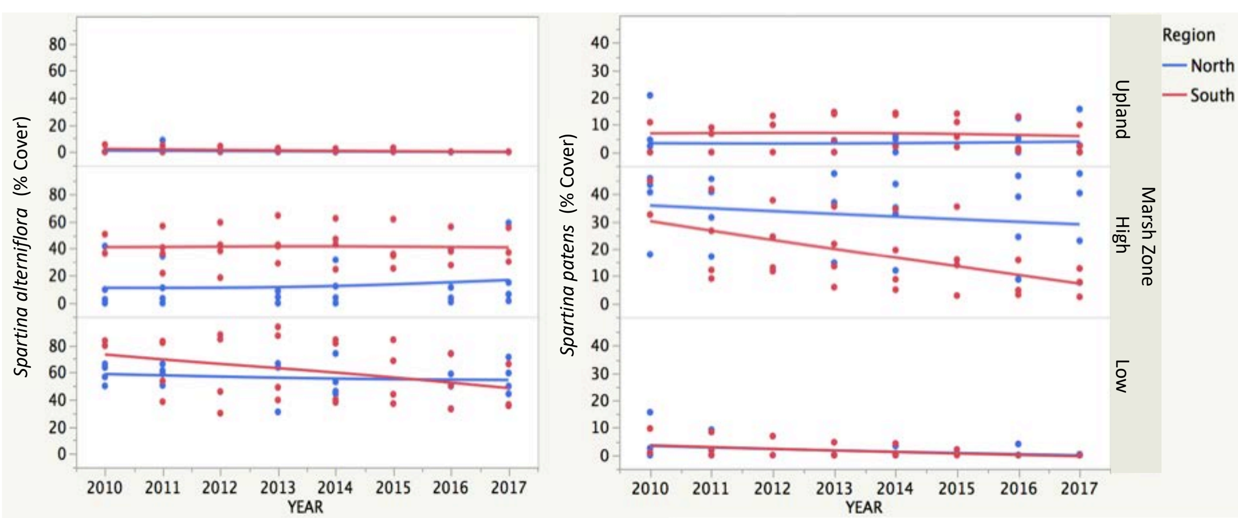

Figure 9. Changes in cover of *Spartina alterniflora* (left) and *S. patens* (right) for Low, High and Upland edge marsh zones (habitats) in southern compared to northern New England Reserves.

Multivariate Community Analyses:

Multivariate analyses detected plant community changes over time at multiple scales. At the New England scale, including data from all eight marshes (four coastal states), we found significant changes indicating increased inundation (Table 5). Overall, the plant community was shifting towards greater *Spartina alterniflora*, which generally tolerates more flooding and is the low marsh dominant for the region (Nixon 1982, Donnelly and Bertness 2001), as well as greater bare cover. In contrast, perennial grass species (*Spartina patens* and *Distichlis spicata*) typical of New England high marshes were found to be decreasing overall. When examining New England by marsh zone, we also detected significant results in the high marsh ($p<0.05$) and a general trend in the low marsh ($p = 0.10$). High marsh communities are becoming more similar to low marshes, with losses of perennial grass cover traditionally dominant in the high marsh (*Spartina patens*, *Juncus gerardii* and *Distichlis spicata*), and gains in *S. alterniflora* and bare cover. At the same time, low marsh communities appear to be transitioning towards less vegetation, with increases in abiotic cover (e.g., bare, dead, water) and decreases in *S. alterniflora* (Table 6).

Table 5. Summary of multivariate PRIMER results for New England. All tests were performed across first and last years of data for each marsh: Great Bay and Narragansett Bay Coggeshall = 2010-2017. Narragansett Bay Nag = 2010 to 2015. Waquoit Bay = 2011-2017 and Wells = 2011-2016. Dark Blue shading indicates significance ($p<0.05$), whereas light blue shading indicates a general trend ($p<0.20$). Sp alt = *Spartina alterniflora*, Sp pat = *Spartina patens*, Di spi = *Distichlis spicata*.

	NEW ENGLAND			
	ANOSIM	NMDS	SIMPER +	SIMPER -
Overall	0.007	X	**Sp alt**, Bare	Sp pat, Di spi
Low marsh	0.103	X	**Water**, Bare, Dead	Sp alt
High marsh	0.023	X	**Sp alt**, Bare	Sp pat, Di spi
Upland edge	0.542			

Table 6. SIMPER results table from New England low marsh, showing the highest cover classes most contributing to dissimilarity (up to 90%) between 2010 and 2017. Blue shading indicates an increase in cover, orange indicates a decrease. Bold font indicates the 4 strongest contributors to dissimilarity.

	Average Cover		Dissimilarity		
Species	1st year	Last year	Avg	%	Cum %
Water	**23.8**	**26.89**	**10.46**	**21.93**	**21.93**
Bare Ground	**33.85**	**37.19**	**10.09**	**21.15**	**43.07**
Spartina alterniflora	**55.03**	**48.24**	**9.42**	**19.75**	**62.82**
Dead	**3.27**	**5.26**	**4.65**	**9.74**	**72.56**
Algae	0.45	3.57	2.37	4.96	77.52
Wrack	2.16	1.43	2.16	4.52	82.04
Spartina patens	2.09	0.71	1.65	3.46	85.5
Salicornia spp	0.34	0.92	1.65	3.45	88.96
Distichlis spicata	1.01	0.13	1.05	2.2	91.15

Data from the four New England Reserves were also analyzed by region: northern macrotidal marshes in NH and ME, southern mesotidal marshes in MA and RI. Multivariate analyses revealed stark differences between northern and southern New England marshes. Results from southern New England were similar to those found overall in New England, with high marsh plots shifting towards low marsh communities and low marsh plots becoming less vegetated – community changes indicative of greater tidal inundation (Figure 10, Table 7). Changes in southern marsh communities were significant overall and within the low and high marsh zones (Table 7). Whereas in northern marshes, shifts were less apparent with only significance found for all marsh zones together, showing increased *S. alterniflora* and bare covers and decreased *S. patens* and dead covers. Such changes have been documented previously (Donnelly and Bertness 2001, Raposa et al. 2017), but this is the first study that we are aware of showing more rapid changes in southern *versus* northern New England salt marshes. Furthermore, when examined using whole plant communities, results support our previous observations using pie-charts and univariate statistical analyses.

Table 7. Summary of multivariate PRIMER results for northern and southern New England. All tests were performed across 1st and last years of data for each marsh (as in Table 5). Dark Blue shading indicates significance ($p<0.05$). Sp alt = *Spartina alterniflora*, Sp pat = *Spartina patens*, Di spi = *Distichlis spicata*.

	NORTHERN NEW ENGLAND				SOUTHERN NEW ENGLAND			
	ANOSIM	NMDS	+ SIMPER	-	ANOSIM	NMDS	+ SIMPER	-
Overall	0.029	X	Sp alt, Bare	Sp pat, Dead	0.004	X	Bare, Water	Sp alt, Sp pat
Low marsh	0.492				0.047	X	Water, Bare, Dead	Sp alt
High marsh	0.282				0.003	X	Sp alt, Bare	Sp pat, Di spi
Upland edge	0.802				0.674			

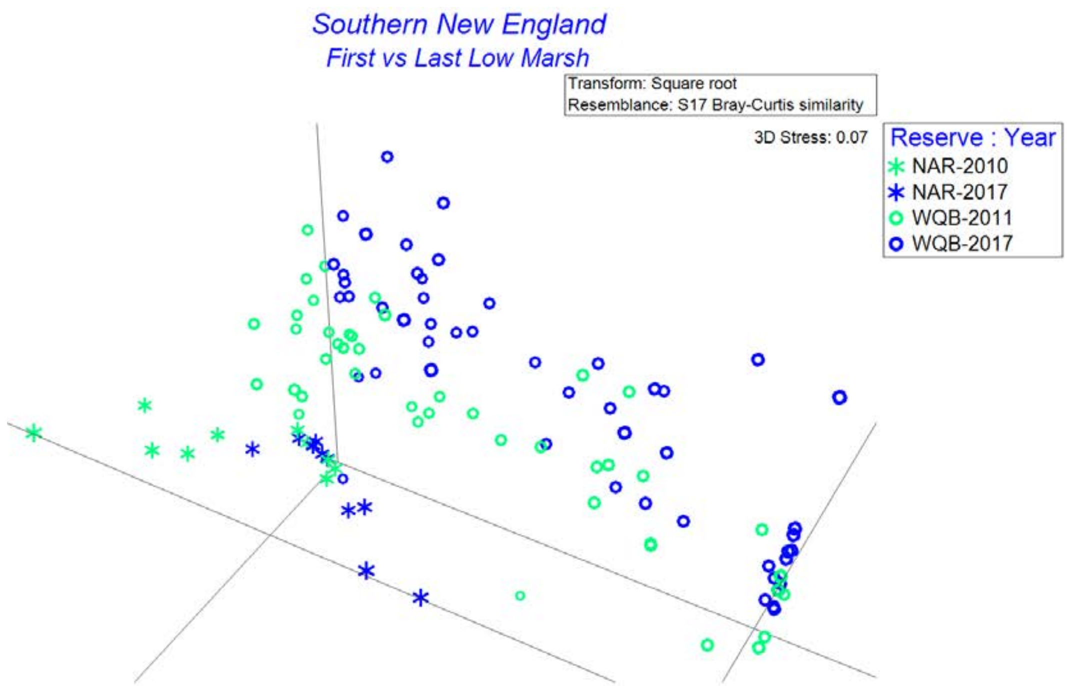

Figure 10. Non-metric multi-dimensional scaling plot of Southern New England low marsh, comparing early vs recent years. NAR = Narragansett Bay, WQB = Waquoit Bay.

Among Reserves, the strongest signal of change came from Narragansett Bay with significant changes found overall and in the low and high marsh (Table 8, Figure 11). One of the biggest drivers of change identified through SIMPER was a large increase in bare cover in both the low and high marsh zones (+20% and +17%, respectively). This large shift came at the expense of plant covers, showing large decreases in dominant species in their respective zones: *S. alterniflora* -14% low marsh, *S. patens* -14% high marsh (Table 9). At Coggeshall marsh, there was a distinct community shift in the high marsh as shown through ordination (Figure 11) and quantified through ANOSIM (p=0.003). A further investigation into all years of data shows this shift became statistically significant in 2014, only 5 years after monitoring began and continued through the last year of data, 2017 (Table 10).

For the other three Reserves, results were less distinct but still showed changes in plant communities that reflect wetter conditions. For instance, the overall marsh ($p = 0.14$) and low marsh ($p = 0.06$) at Waquoit Bay showed a general trend that mirrored the patterns found in Narragansett Bay. Marshes were becoming wetter and less vegetated, especially so in the low marsh. The community trends for Waquoit Bay marshes is supported by statistically significant univariate analyses that can be found in Appendix B.

Table 8. Summary of multivariate PRIMER results for Narragansett Bay. All tests were performed across 1st and last years of data for each marsh: Coggeshall 2010 to 2017, Nag 2010 to 2015. Dark Blue shading indicates significance ($p<0.05$). Sp alt = *Spartina alterniflora*, Sp pat = *Spartina patens*, Di spi = *Distichlis spicata*.

	Narragansett Bay			
	ANOSIM	NMDS	+ SIMPER	-
All Plots	0.001	X	Bare	**Sp alt**, Sp pat, Di spi
Low Marsh	0.016	X	Bare	**Sp alt**, Sp pat, Di spi
High Marsh	0.002	X	**Bare**, Sp alt	Sp pat, Di spi
Upland Edge	0.597			

Table 9. SIMPER results table from Narragansett Bay low and high marsh, showing the cover classes most contributing to dissimilarity (up to 90%) between 2010 and 2017 for Coggeshall and 2010 and 2015 for Nag. Blue shading indicates an increase in cover, orange indicates a decrease.

	Average Cover		Dissimilarity		
Species	2010	2017*	Avg	%	Cum %
	Low Marsh				
Bare Ground	10.27	31.05	12.57	44.49	44.49
Spartina alterniflora	81.18	67.11	5.55	19.64	64.13
Spartina patens	4.58	0.86	4.03	14.27	78.4
Distichlis spicata	3.69	0	3.39	12.01	90.41
	High Marsh				
Bare Ground	5.51	22.79	11.69	26.15	26.15
Spartina patens	39.9	26.22	11.38	25.45	51.6
Spartina alterniflora	42.26	43.85	11.3	25.28	76.88
Distichlis spicata	11.66	5.94	7.45	16.68	93.56

Table 10. ANOSIM summary table for Coggeshall low marsh in Narragansett Bay for all years. Blue shading indicates greater significance between years.

Years	p value
2010, 2011	0.600
2010, 2012	0.506
2010, 2013	0.428
2010, 2014	0.032
2010, 2015	0.006
2010, 2016	0.019
2010, 2017	0.003

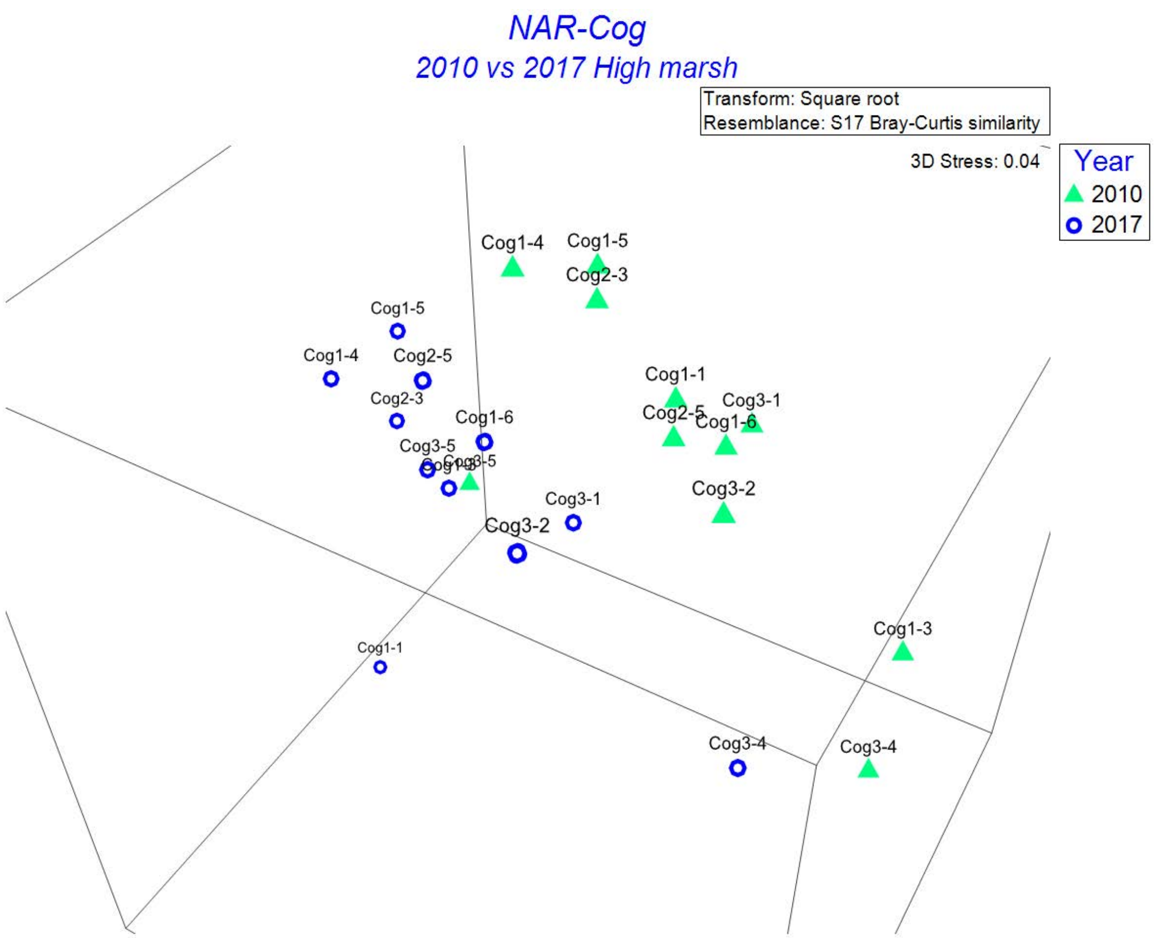

Figure 11. Non-metric multi-dimensional scaling plot of Coggeshall low marsh samples in Narragansett Bay. Symbols are labeled with plot IDs.

Moving north, significant differences in plant communities in Great Bay, NH between 2010 and 2017 were detected for the overall marsh (p=0.026) and for the transition (p=0.001), where plots at the boundary of low and high marsh zones were sampled. The most notable significant differences were detected in transition zone plots: S. *alterniflora* + 25% cover, *S. patens* - 5% (Figure 12, Table 11). Furthest north, at the Wells Reserve, no significant changes in the plant communities were found (p=0.646), however, there appeared to be a general trend in the high marsh (p=0.13) resulting from increases in *S. alterniflora* and unvegetated cover, primarily at the expense of *S. patens* and *Plantago maritima.* Again, the univariate results finding the SA:SP ratio increased over time (see Appendix B) corroborate the community trend found in the Webhannet Estuary.

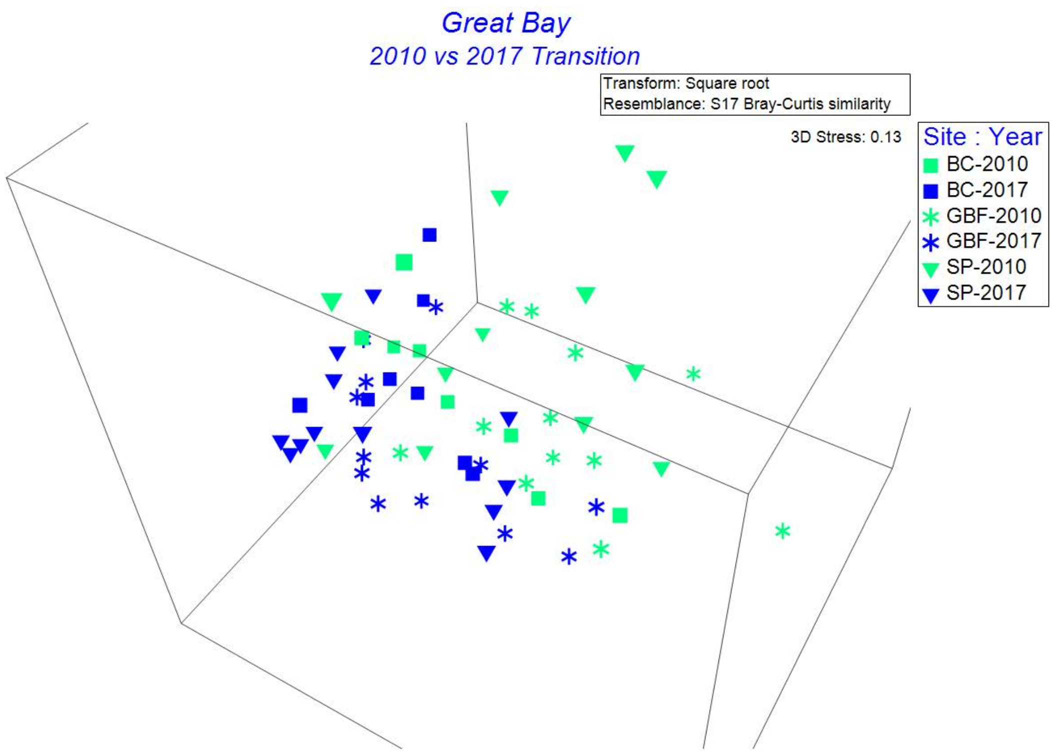

Figure 12. Non-metric multi-dimensional scaling plot of Great Bay transition plots (placed at the boundary of low and high marsh zones).

Table 11. SIMPER results from Great Bay, NH transition plots located at the boundary of low and high marsh, showing the highest cover classes most contributing to dissimilarity (up to 90%) between 2010 and 2017. Blue shading indicates an increase in cover, orange indicates a decrease. Bold font indicates the 4 strongest contributors to dissimilarity.

	Average Cover		Dissimilarity		
Species	2010	2017	Avg	%	Cum %
Spartina patens	**16.27**	**10.97**	**8.59**	**16.76**	**16.76**
Spartina alterniflora	**34.66**	**59.38**	**8.1**	**15.8**	**32.56**
Bare Ground	**16.61**	**16.42**	**6.93**	**13.52**	**46.08**
Dead	**12.72**	**1.06**	**6.31**	**12.31**	**58.39**
Wrack	9.59	1.38	5.22	10.19	68.58
Distichlis spicata	4.22	6.5	4.83	9.43	78.01
Water	9.06	1.72	3.42	6.67	84.68
Atriplex patula	4.41	0.06	2.29	4.47	89.15
Limonium nashii	0.41	0.73	1.41	2.75	91.9

Inundation Modeling:

The 'early' and 'recent' periods represent a five to six-year window that coincides with a sharply increasing phase of the lunar nodal cycle (i.e., Metonic cycle). This predictable cycle peaked in 2015, a year before the Wells and Narragansett Bay 'recent' surveys. This is an important factor to consider when evaluating the inundation results as the magnitude and duration of tidal flooding are high due to both natural cycles (lunar nodal) and anthropogenically enhanced sea level rise. Near term, future inundation analyses will conversely encompass a sharply declining phase of the nodal cycle thus likely producing less dramatic results due to the dampening effect of the declining natural cycle in conjunction with local relative sea level rise rates.

When comparing changes in vegetation cover over time (early vs. recent), the percent cover of *S. alterniflora* appears to have slightly decreased and has become more restricted to plots that are less frequently inundated at both Narragansett Bay and Waquoit Bay (Figures 13 and 14). The amount of bare or dead cover is relatively higher in the recent time period for all sites, with increases in abiotic cover occurring across all inundation regimes, particularly at Waquoit Bay (Figure 14). The recent time period also generally exhibits less cover of *S. patens* and the distribution is becoming more restricted at all of the sites (Figures 13-15). For the flood sensitive species (total cover of *S. patens, D. spicata,* and *J. gerardii*), cover has trended downward in the recent surveys and there may have been a shift to less flooded plots over time at Narragansett Bay and Waquoit Bay (Figures 13 and 14).

Across the three Reserves included in the analysis (Narragansett Bay, Waquoit Bay, Wells), some general, marsh-wide results are apparent. Overall, it appears that the percent cover of *S. alterniflora* has decreased in recent surveys and is becoming more restricted to less frequently flooded plots. At the same time, the flood sensitive species have also decreased in cover and the elevation distribution has become even more restricted over time (Figure 16). These findings are consistent with our other analyses as well as previous studies conducted in New England showing that *S. patens* and other flood sensitive species are being replaced by *S. alterniflora* as it migrates into the formerly "high marsh zone " which is above the elevation of mean high water (Donnelly and Bertness 2001, Raposa et al 2017, Watson et al. 2017b, Gonneea 2019) and suggests that inundation due to sea level rise is a key driver in vegetation shifts and loss at lower elevations (Watson et al. 2017b). Further, the amount of bare ground has increased at all of the Reserves, suggesting vegetation dieback or an increase in interior ponding, which may be especially detrimental in the microtidal marshes of Narragansett Bay and Waquoit Bay (Kearney and Turner 2016, Watson et al. 2017). As sea levels continue to rise and the landward migration of *S. alterniflora* replaces the high marsh plant communities, understanding the impact of increased inundation on vegetation community composition will help coastal resource managers plan for salt marsh protection and restoration. This is especially pertinent with respect to declining tidal marsh nesting birds that rely on infrequently flooded marsh vegetation for fledging their young (Correll et al. 2016).

Marsh Surface Elevation:

Surface elevation tables (SETs) were measured at all Reserves, including 7 of the 8 marshes highlighted in this report. Data from the three Reserves that had multiple stations within sentinel site marshes are reported here (Table 12). The Great Bay Reserve also measured sediment accretion above marker horizons to yield an estimate of belowground subsidence. Subsidence can be thought of as the compaction and breakdown of underlying peat deposits and ranged from 0.2 to 1.1 mm/yr in Great Bay. Using the two Narragansett Bay marshes as an example, SET data are graphically displayed in Figure 17. In order to clearly see the change in marsh surface elevation over time, data are offset along the Y-axis, which is then labeled relative elevation.

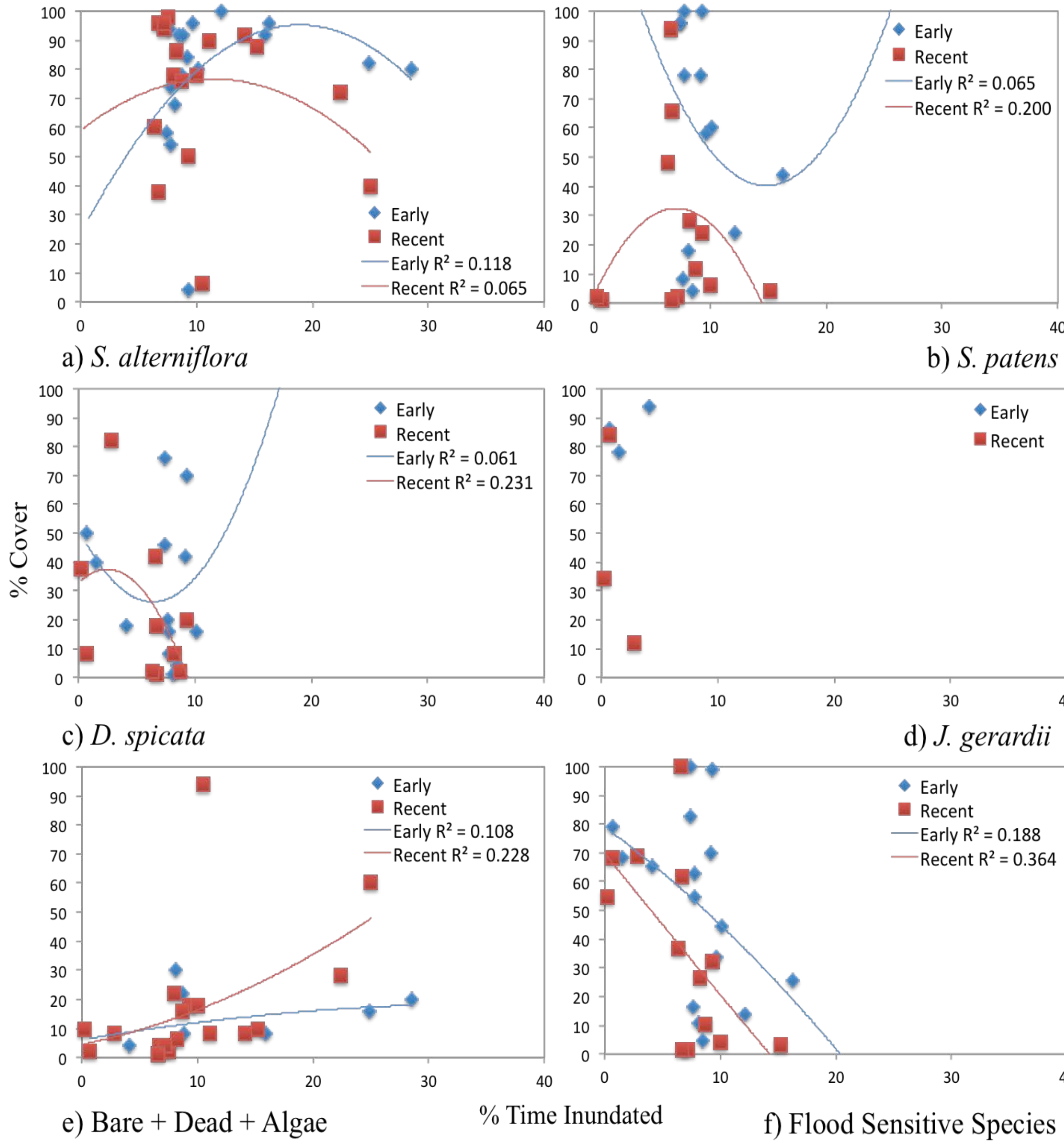

Figure 13. Percent cover vs. percent time inundated shown with best fit, but not statistically tested, polynomial models at Coggeshall Marsh, Narragansett Bay for (a) *Spartina alterniflora*; (b) *Spartina patens*; (c) *Distichlis spicata*; (d) *Juncus gerardii*; (e) Bare + Dead + Algae; and (f) Flood sensitive species. Note: the percent covers of the flood sensitive species were normalized to 100 percent. The best fit polynomial curves were omitted for *J. gerardii* due to insufficient data.

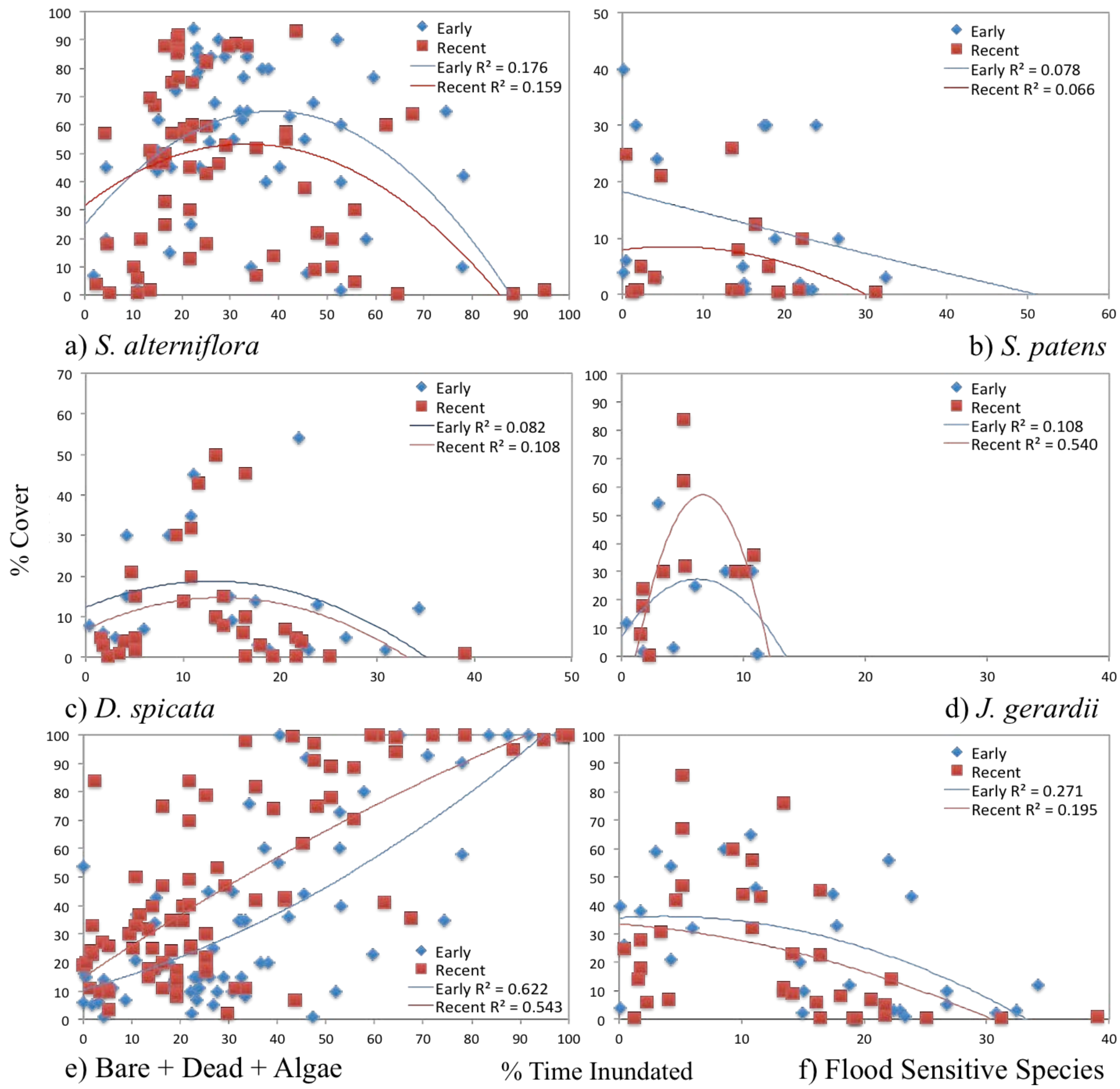

Figure 14. Percent cover vs. percent time inundated shown with best fit, but not statistically tested, polynomial models at Sage Lot Pond marshes in Waquoit Bay for (a) *Spartina alterniflora*; (b) *Spartina patens*; (c) *Distichlis spicata*; (d) *Juncus gerardii*; (e) Bare + Dead + Algae; and (f) Flood sensitive species.

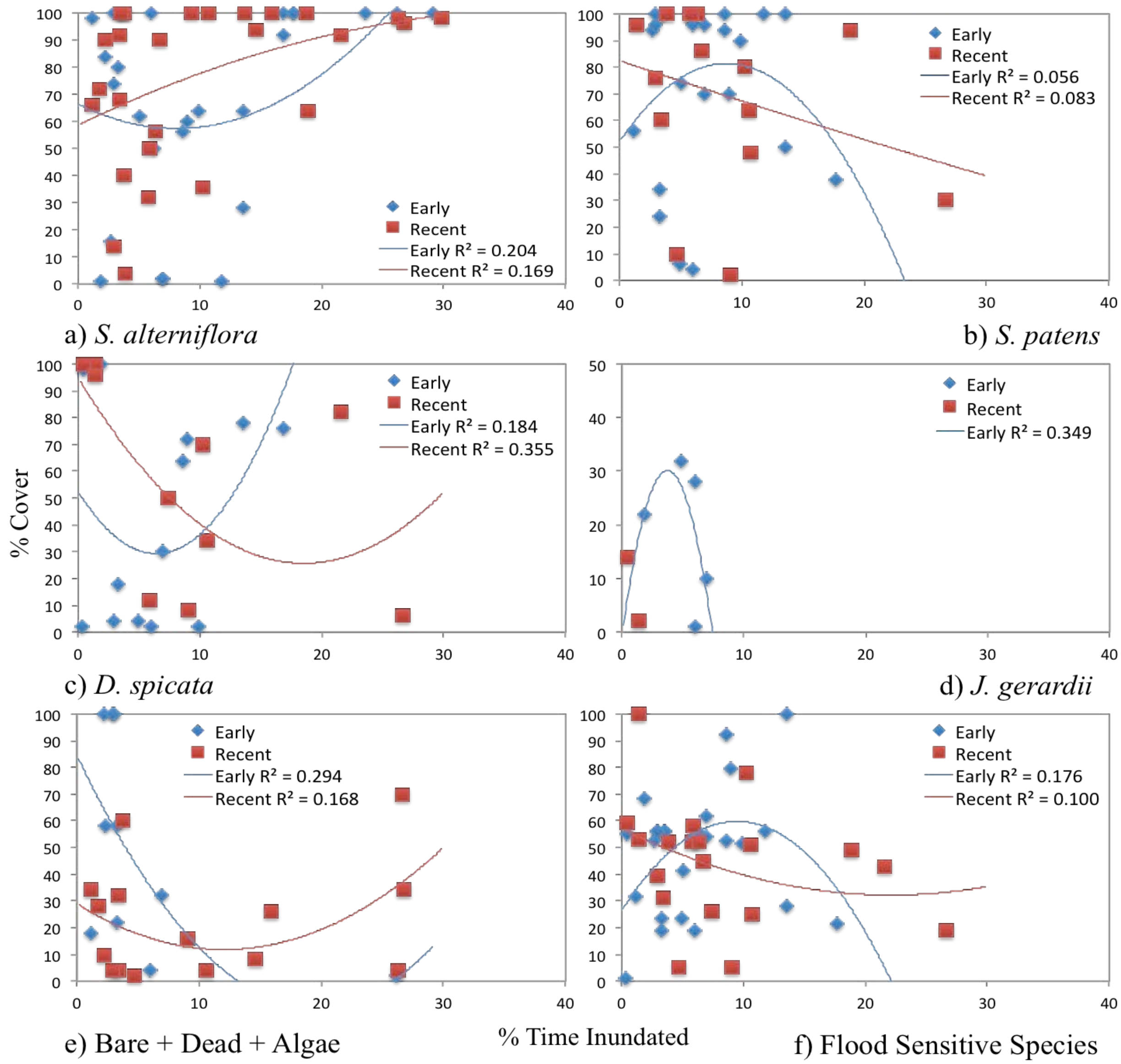

Figure 15. Percent cover vs. percent time inundated shown with best fit, but not statistically tested, polynomial models at Webhannet Marsh in Wells for (a) *Spartina alterniflora*; (b) *Spartina patens*; (c) *Distichlis spicata*; (d) *Juncus gerardii*; (e) Bare + Dead + Algae; and (f) Flood sensitive species. Note: percent cover can be greater than 100% due to point intercept sampling method used in Wells. Note: the percent covers of the flood sensitive species for Narragansett Bay and Wells were normalized to 100 percent. The best fit polynomial curve was omitted for recent *J. gerardii* due to insufficient data.

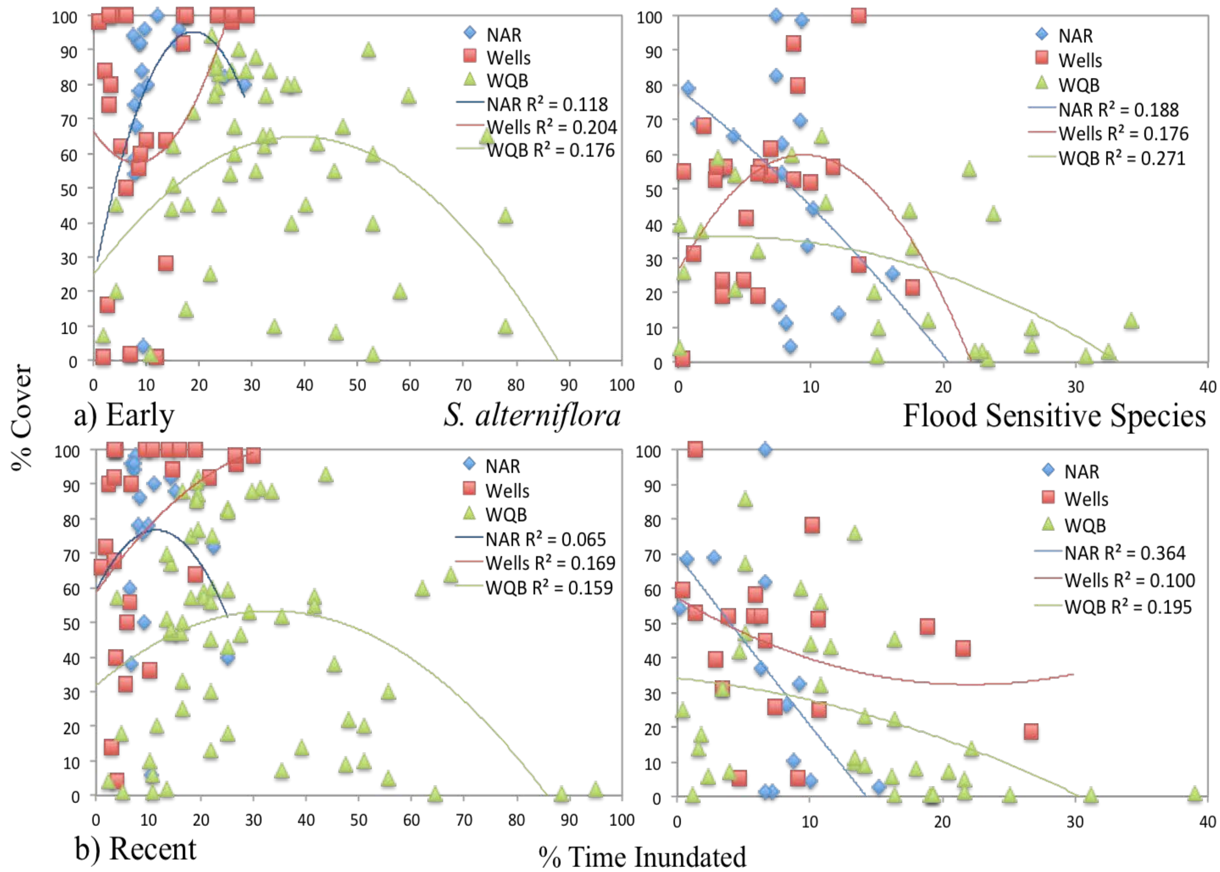

Figure 16. Comparison of *Spartina alterniflora* and flood sensitive species between Reserves for (a) early; and (b) recent monitoring periods. Best fit polynomial curves are shown to help guide visual interpretation of the data. Note: the percent cover of the flood sensitive species for Narragansett Bay and Wells were normalized to 100 percent.

Table 12. Results from Surface Elevation Tables (SETs) and Marker Horizons at biomonitoring sites showing elevation increase and comparing it to SLR for the same time period (2010-2017) from tidal data at Wells ME (https://tidesandcurrents.noaa.gov/waterlevels.html?id=8419317).

			Rate of Change (mm/year)					
Reserve	**Marsh**	**n**	**Surface Elevation Increase**	**Error**	**Marker Horizon Accretion**	**Subsidence (by difference)**	**Difference from SLR @ Wells 3.23**	**Result**
Great Bay	**Sandy Point**	5	3.2	0.5	3.4	0.2	**0.0**	**EQUAL**
	Great Bay Farms	3	1.9	0.2	3.0	1.1	**-1.3**	**LOSING**
Waquoit	**SLP Dune Edge (Section 1)**	4	2.5	0.7			**-0.8**	**LOSING**
	SLP Forest Edge (Section 2)	4	3.0	0.7			**-0.2**	**EQUAL**
Narragansett	**Coggeshall**	6	1.1	0.3			**-2.1**	**LOSING**
	Nag	6	2.1	0.7			**-1.1**	**LOSING**

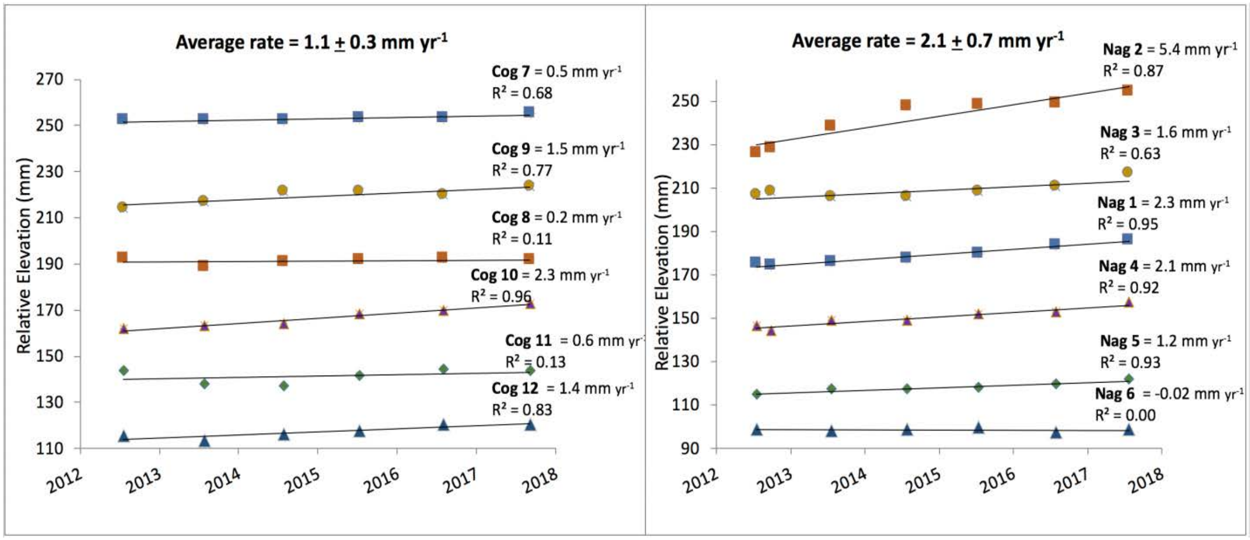

Figure 17. Elevation change determined using Sediment Elevation Tables (SETs) for two marshes in Narragansett Bay: Coggeshall Marsh (left) and Nag Marsh (right). Data from the 12 numbered replicates are regressed over time and are offset along the Y-axis to improve readability.

Generally, the increase in marsh elevation varied by marsh. For example, both marshes in Narraganset Bay lost elevation relative to regional sea level rise (3.23 mm/yr; Wells ME station #8419317 at https://tidesandcurrents.noaa.gov/waterlevels.html?id=8419317), whereas, both Great Bay and Waquoit Bay had one marsh with a rate of elevation gain similar to SLR and one less than SLR (Table 12). While we recognize that the SLR calculated for 2010 to 2017 at Wells, ME may not reflect local SLR rates at the other Reserves (e.g., 5.26 mm/yr for 1999-2015 in Narragansett Bay - Raposa et al. 2016a), it provides a reasonable average, matching recent rates calculated by others (e.g., 3.26 mm/yr - Nichols and Cazenave 2010, 3.3 mm/yr - Beckley et al. 2017). Overall, marshes across New England were found to be building, but many were not building fast enough relative to SLR to maintain their position in the tidal frame. It is important to note the variation between SET results within a single marsh (Figure 17), showing different parts of the marsh are building at different rates and several SETs may be needed to document marsh accretion and building over time.

Monitoring Recommendations

Based on our analysis, we recommend that moving forward the following data collection and recording practices outlined in Table 13 be adopted. These suggestions will allow data to be more easily combined for New England and other Reserves around the country in the future. For vegetation, we recommend annual monitoring at the height of the biomass, August to mid-September, for New England. Marshes with more stable communities and low interannual variation could be sampled with lower frequency but annual sampling is strongly recommended to maximize the signal to noise ratio that can be decreased by interannual variability. All New England Reserves consistently used a 1 m^2 quadrat spaced along transects, in line with national protocols (Moore 2013). Transects should span the marsh, from mudflat or main tidal creek to upland. Ecotones, the borders between habitat types, may change more rapidly than the marsh as a whole and specific monitoring protocols for ecotones could provide valuable information for Reserves, regions and across the NERR system (Moore 2013).

The two most used measures of plant abundance, Point Intercept and Ocular Cover, both can be used to show vegetation change, but it is easier to combine data within a region if the same method is used. Within the cover categories, several suggestions are included in Table 13. These range from assessing algae, wrack, bare and dead as distinct cover classes, to including water and overstory as potentially important subsidiary measures (but not included in the 100 percent of cover totals). Algae should be identified as specifically as possible so future invasions and blooms can be documented. Plant height was measured using a variety of techniques; we do not have a recommendation at this point in time. Perhaps in the future, collections using multiple methods might help develop the best metric and protocol for the specific question asked. Shoot density of the dominant plants did not show clear changes over time in our analyses; data collected over longer time periods and other regions might produce valuable results, but this metric also needs critical evaluation.

Beyond vegetation and cover types, water levels, plot elevations and Surface Elevation Tables with Marker Horizons were found to be valuable metrics to characterize marsh condition and change. Water level records are typically obtained using pressure transducers that should be placed at the lowest possible elevation to capture low tide. Water level measurements should be periodically collected during the growing season, (at least one complete lunar cycle: 29 days) and be coordinated with plot elevations (every 3 to 5 years) referenced to the same datum to allow inundation analysis. Surface Elevation Tables (SETs) and marker horizons (MHs) have a clear, national protocol that should be followed (Lynch et al. 2015), but variability between stations suggests more than three may be needed to characterize changes in a particular marsh. If collected together once at the same time each year, SET+MH will show marsh elevation change as the net result of sediment accretion at the surface and peat subsidence.

Table 13. Plant community method variations for New England NERRs. For transects, "U----W" spans the marsh from upland edge to the main tidal water body, "U---c" extends from upland edge to a tidal creek within the marsh interior. For plant cover estimates, PI = point-intercept and OC = ocular cover. For ecotone monitoring, PL (Plots) = additional plots within habitat borders, BO (Boundaries) = horizontal shifts in zones/plants along transects. For plant heights, "4/5" = the height at which 1/5 of the shoots will be taller for each dominant species (e.g., *S. alterniflora, S. patens,* etc.), "12" = 12 haphazardly selected shoots for each dominant, 3 at each corner of the quadrat, "3T" = measuring the 3 tallest shoots for each dominant at a designated quadrat corner. SET refers to surface elevation table.

New England National Estuarine Research Reserves					
	GRB	**NAR**	**WQB**	**WEL**	**Recommendations**
Transects	U------W	U------W	U------W	U-----c	Establish transects spanning entire marsh
Plots	$1m^2$	$1m^2$	$1m^2$	$1m^2$	0.5 to $1m^2$. If different, target similar total area monitored. e.g., 20, $1m^2$ plots = 40, $0.5m^2$ plots
Frequency	Annually	Annually	Annually	Biennially	Annual or biennial; longer with stable plant communities
Ecotones	PL	BO	PL		No recommendation. Regional consistency preferred. Trade off between time (BO) and information (PL).
Plant Cover	OC	PI	OC	PI	No recommendation. Regional consistency preferred. Trade off between time (OC) and information (PI)
Algae	X		X		Record live algae. Drift algae 'unrooted' should be classified as wrack
Bare	X	X	X	X	Record. Note difficulty making comparisons across plant cover method (PI, OC)
Dead	X		X		Record as a distinct cover class, separately from bare
Water	X		X		Record 'standing' water near low tide only. Analyze separately (does not contribute to total cover)
Wrack	X	X	X		Record. Then remove and assess vegetation before replacing
Overstory	X		X		Record total overstory as a percentage. Analyze separately (does not contribute to total cover)
Plant Height	4/5	12	12	3T	No recommendation. Regional consistency preferred. Statistical analysis of variability conducted on plots utilizing multiple methods is needed.
Plant Density	X		X	X	No recommendation. Regional consistency preferred. Dominant marsh species and potential value may differ regionally and nationally
Water levels	X		X	X	Monitor during growing season; 6 minute intervals, every 3-5 years with plot elevations
Plot elevations	X*	X	X	X	3-5 years monitoring frequency
SETs	X	X	X	X	Annual frequency
Marker horizon	X	X			Annual frequency to parse out surface/sub-surface elevation changes

Summary and Conclusions

Salt marshes have been building and expanding during a period of slow sea level rise across much of the northeastern US even as human impacts have reduced their overall area and health due to a variety of stressors (Geden et al. 2009, Burdick and Roman 2012). Rapid changes in climate, especially accelerated rates of sea level rise, may pose the greatest threat to marshes because these poised systems depend upon feedbacks that are highly sensitive to flooding (Raposa et al. 2017, Watson et al. 2017b). Tracking changes in marsh vegetation communities provides a powerful and informative approach to monitoring the impacts of SLR (Kennish 2002, Raposa et al. 2016), which the NERRs have done with Sentinel Site Monitoring since 2010. The long-term NERRS Sentinel Site project was developed to monitoring the response of salt marsh plant communities to climate change, sea level rise, and other human actions such as tidal restoration and development in adjacent uplands. Our analysis focused on tidal marsh responses to sea level rise using data from marshes relatively unimpacted by local human activities.

Sentinel Site data from the four New England Reserves was standardized and compiled into a uniform spreadsheet amenable to a variety of statistical analyses. Disparities among collection methods were identified and recommendations were made to standardize most all protocol components. Correction procedures were developed for those components with irreconcilable differences in field protocols so that regional comparisons could be made.

Over all four New England Reserves combined, temporal trends in plant abundance indicate marshes are responding to sea level rise. Low marshes are becoming less vegetated, the low marsh dominant, *S. alterniflora*, is advancing into the high marsh, and typical high marsh species are becoming less abundant. These trends were found within individual Reserves as well. Previous work in Connecticut (Warren and Niering 1993), Rhode Island (Donnelly and Bertness 2001, Raposa et al. 2016b, 2017, Watson et al. 2017b) and Massachusetts (Smith 2009, 2015) attribute similar trends over time to sea level rise. Using consistent methods, our results detail patterns in vegetation associated with accelerated sea level rise across Reserves in four New England states, strengthening the case for widespread impacts from global warming. Most importantly, plant community changes indicating an increasingly wetter environment that had been documented previously by others in southern New England marshes are consistent with our results in southern as well as northern New England tidal marshes. Further, inundation analysis at three reserves showed plants 'moving' to higher ground as sea levels rise, because, as the SET results indicate, marsh elevations are not building quickly enough to keep pace with current rates of sea level rise.

Several stakeholders within and external to the Reserve System asked us to identify the most valuable monitoring metric, one that is relatively easy to measure and clearly shows impacts from climate change, specifically sea level rise. Our data from permanent plots (identified at the outset as low, high and upper edge habitat zones) of plant cover by species most strongly supports the hypothesis that sea level rise is causing greater flooding and plant responses in tidal marshes of four New England estuaries. Water levels, plot elevation, marsh building and subsidence (using SETs), plant stem density and height were examined, but the most sensitive univariate indicator was the SA:SP ratio (proportion of *Spartina alterniflora* relative to *Spartina alterniflora* and *S. patens* combined), and the best multivariate indicator was the changes in plant community shown by ANOSIM and SIMPER.

Within and across reserves, the stories revealed by the Sentinel Site data, using graphics, traditional univariate analyses and multivariate approaches can help everyone understand the changes in the marshes and the threats they face. Our results serve as a call to action by coastal resource managers, especially those who might be uncertain whether marshes are truly at risk. In anticipation of further marsh impacts due to inundation from accelerating increases in sea level rise, managers should consider increasing the resiliency of our marshes. Hydrology and sediment sources, disrupted by a variety of human actions, need to be restored to marshes, innovative adaptation actions should be tested and if successful in improving resilience to sea level rise, applied to a prioritized set of marshes, and potential marsh migration paths should be identified, protected and enhanced.

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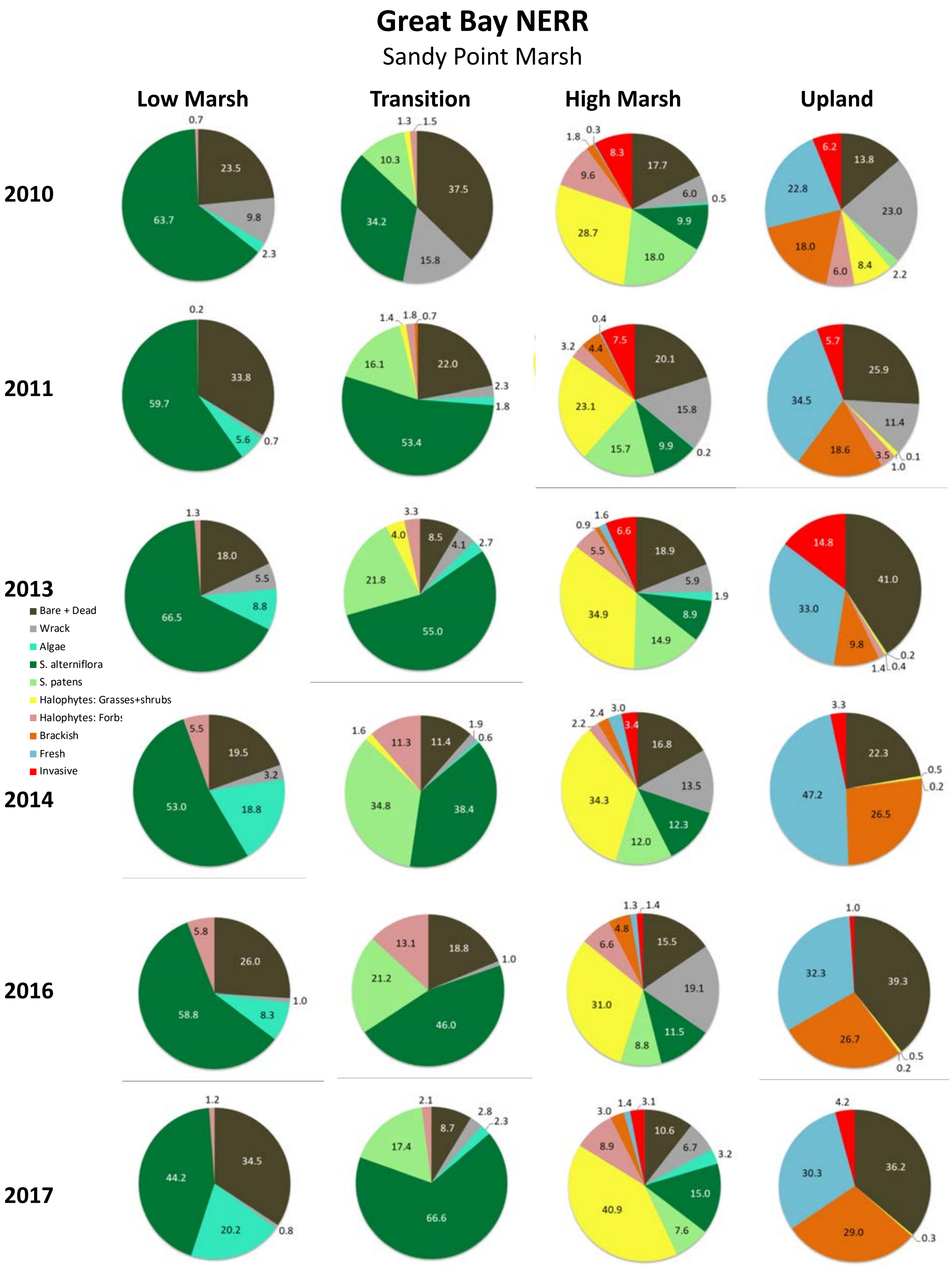
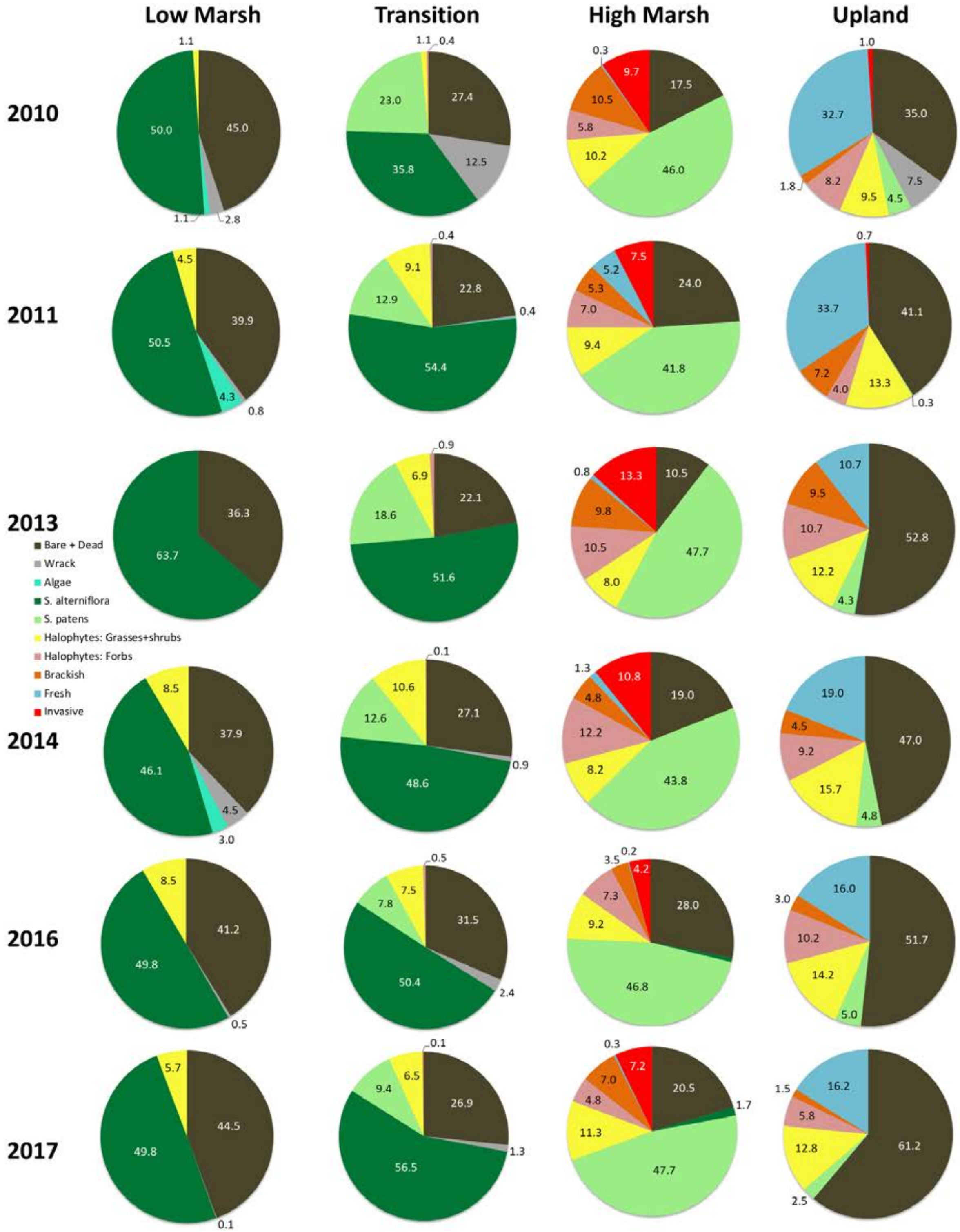
Appendix A Pie Chart Visualizations



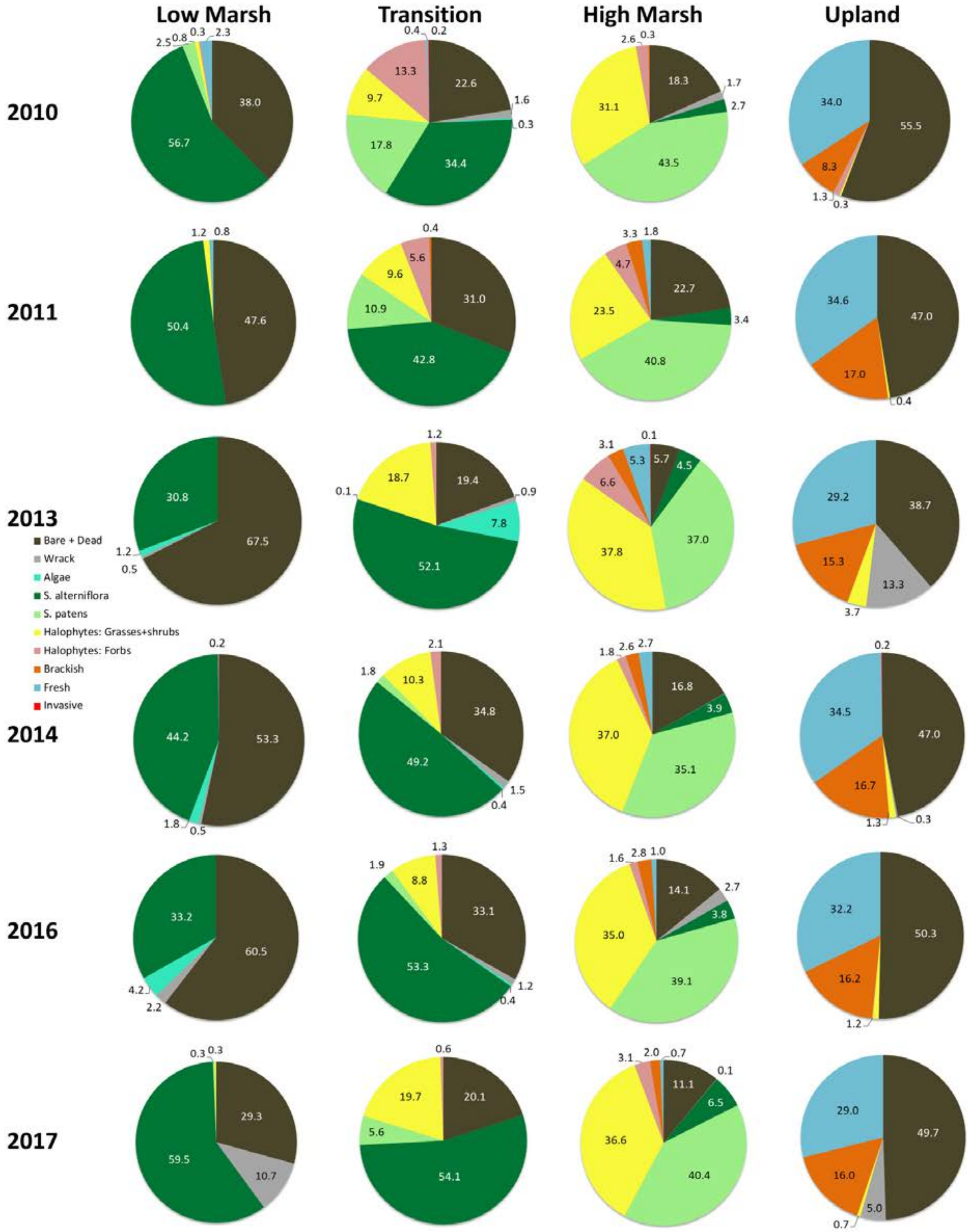
Great Bay NERR

Bunker Creek Marsh



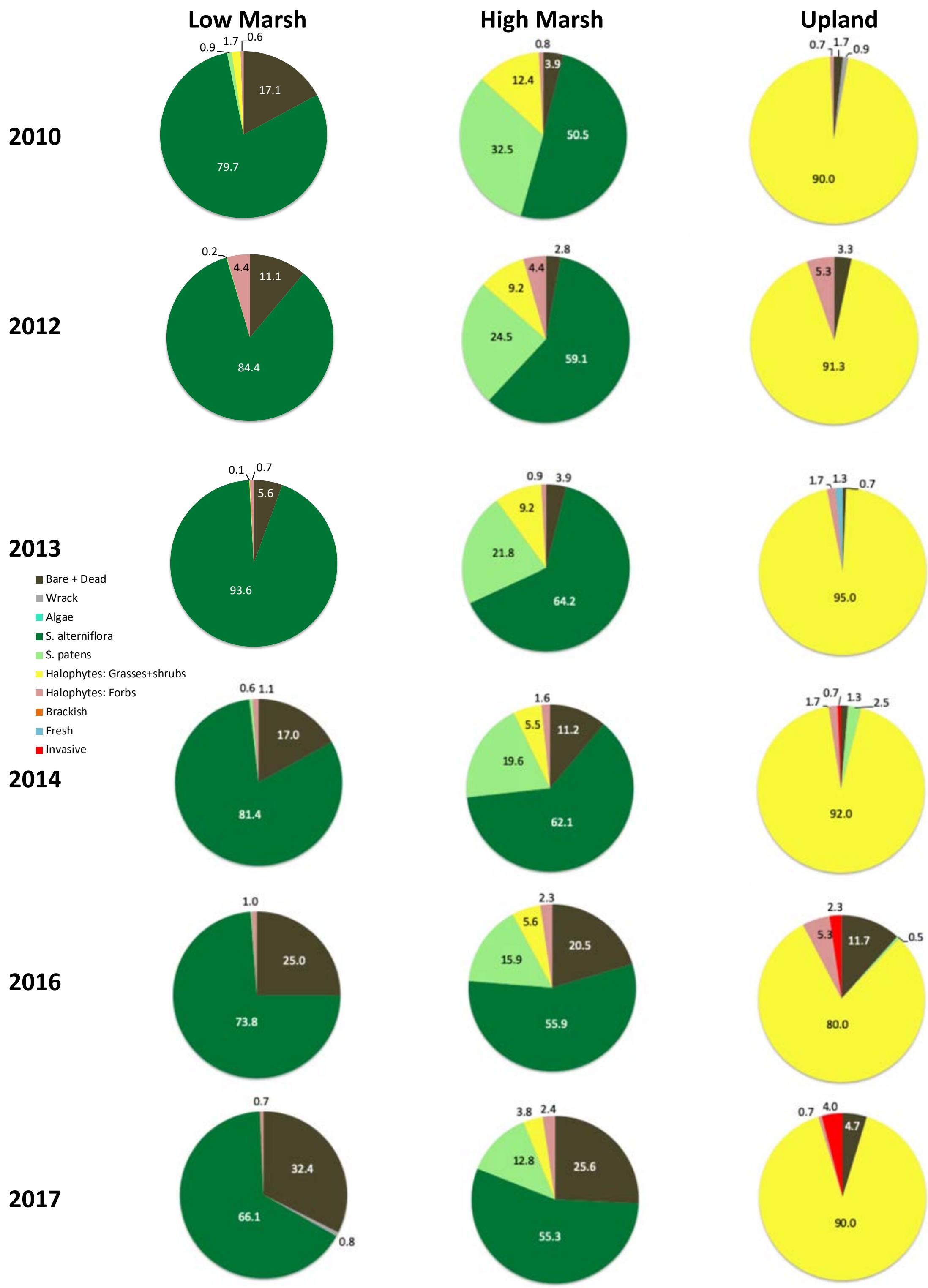
Great Bay NERR

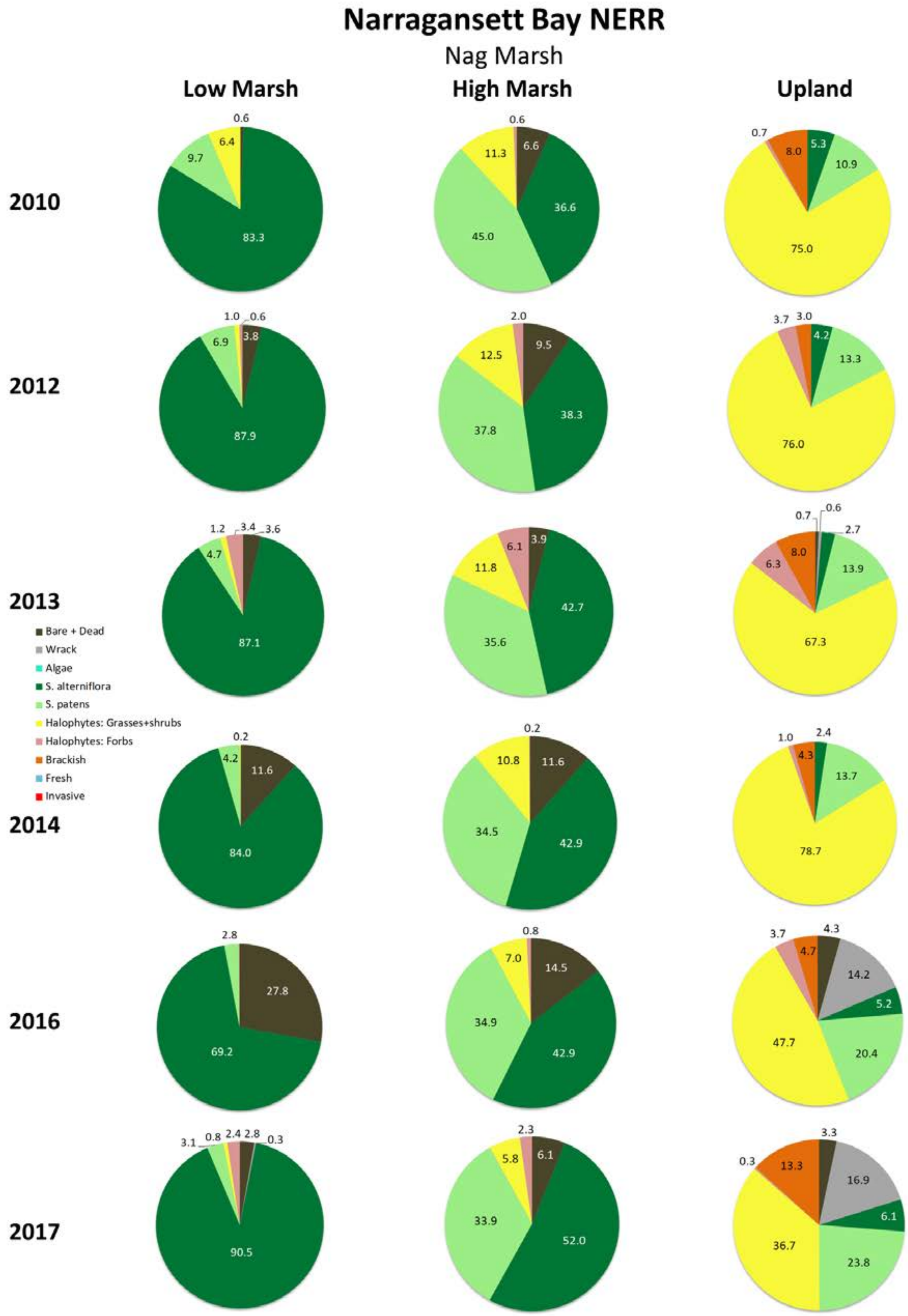
Great Bay Farms Marsh



Narragansett Bay NERR

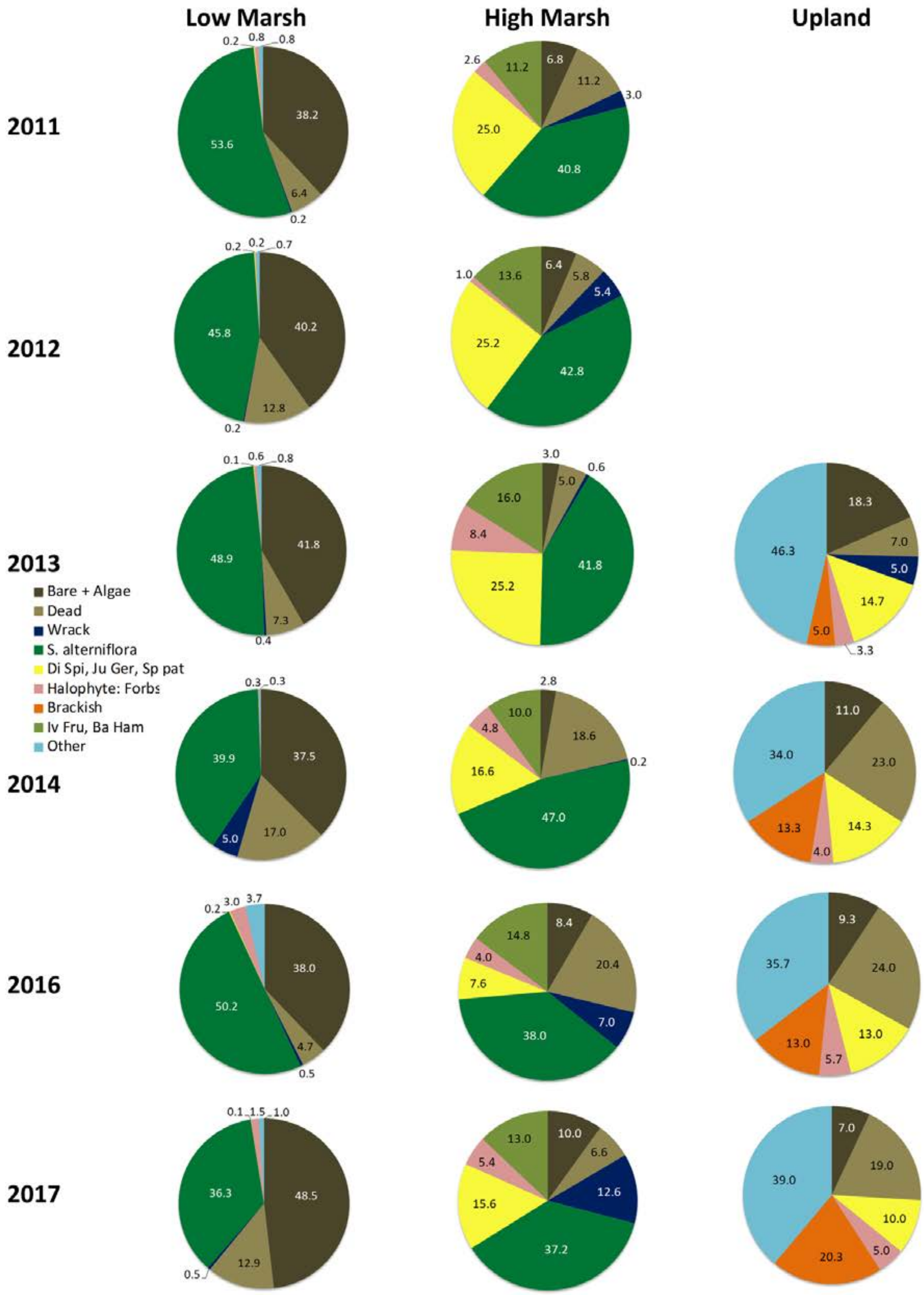
Coggeshall Marsh

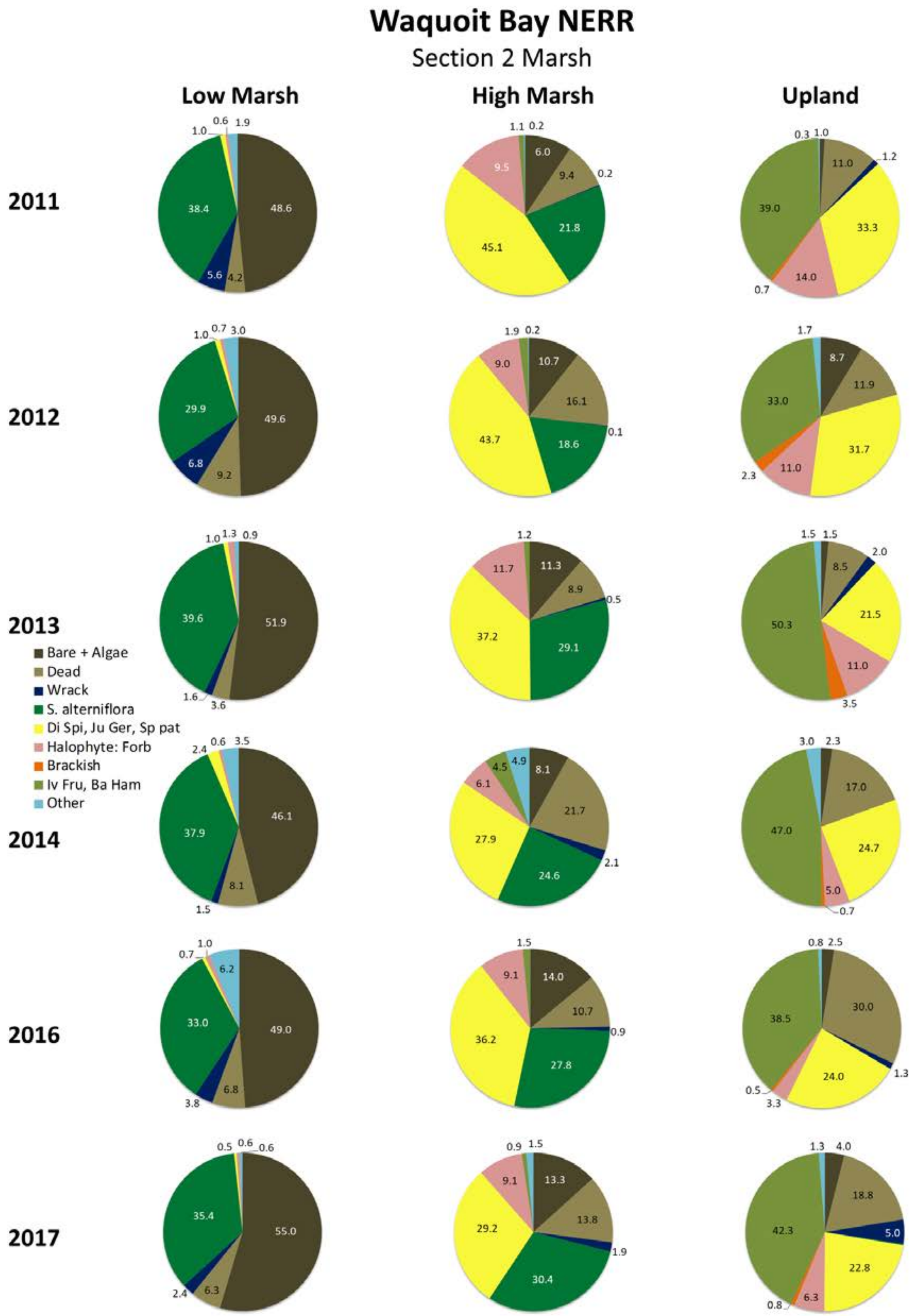



Narragansett Bay NERR
Nag Marsh
Low Marsh
High Marsh
Upland
2010
0.6
6.4
9.7
83.3
0.6
11.3
6.6
36.6
45.0
0.7
8.0
5.3
10.9
75.0
2012
1.0
0.6
6.9
3.8
87.9
2.0
12.5
9.5
38.3
37.8
3.7
3.0
4.2
13.3
76.0
2013
1.2
3.4
3.6
4.7
87.1
6.1
3.9
11.8
42.7
35.6
0.7
0.6
2.7
8.0
6.3
13.9
67.3
Bare + Dead
Wrack
Algae
S. alterniflora
S. patens
Halophytes: Grasses+shrubs
Halophytes: Forbs
Brackish
Fresh
Invasive
2014
0.2
4.2
11.6
84.0
0.2
10.8
11.6
34.5
42.9
1.0
2.4
4.3
13.7
78.7
2016
2.8
27.8
69.2
0.8
7.0
14.5
34.9
42.9
3.7
4.3
4.7
14.2
5.2
47.7
20.4
2017
3.1
0.8
2.4
2.8
0.3
90.5
2.3
5.8
6.1
33.9
52.0
3.3
0.3
13.3
16.9
6.1
36.7
23.8

Waquoit Bay NERR

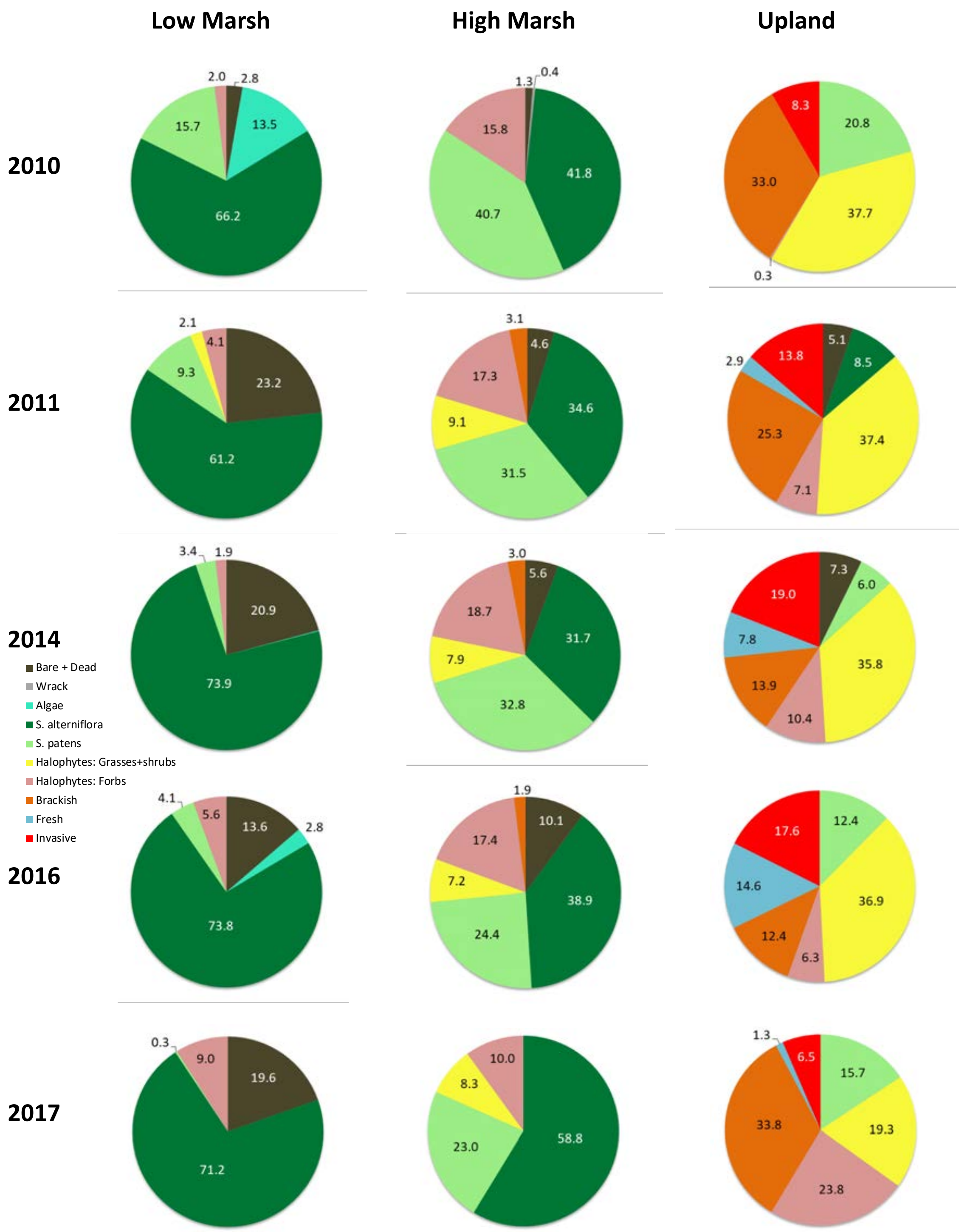
Section 1 Marsh




Waquoit Bay NERR
Section 2 Marsh
Low Marsh
High Marsh
Upland
2011
2012
2013
2014
2016
2017
Bare + Algae
Dead
Wrack
S. alterniflora
Di Spi, Ju Ger, Sp pat
Halophyte: Forb
Brackish
Iv Fru, Ba Ham
Other

Wells NERR

Webhannet River Marsh



Appendix B. Univariate Results by Reserve

Prudence Island, Narraganset Bay NERR:

The two marshes on Prudence Island, Coggeshall and Nag, varied in cover of *Spartina* grasses, with less *S. alterniflora* and more *S. patens* in the Nag high marsh (Table B-1, Figure B-1). Therefore, Nag marsh appears to be less flooded and able to support more high marsh plants, which support previous comparisons showing Nag marsh at higher elevation than Coggeshall (Raposa et al. 2016b). In terms of trends over time, however, both marshes exhibited declines in *S. alterniflor*a in the low marsh and declines in *S. patens* in the high marsh. These trends had been previously identified (Donnelly and Bertness 2001, Raposa et al. 2017), but the time period is lengthened here. Further, the vegetation change is accentuated in the SA:SP ratio, with the proportion of *S. alterniflora* equaling or surpassing *S. patens* in the high marsh during this sampling period for both marshes. Both Spartinas and the SA:SP ratio showed significant differences due to the Year by Marsh Zone interaction, substantiating the aforementioned changes within zones over time. Total cover of the three high marsh specialists: *S. patens, Distichlis spicata* and *Juncus gerardi,* was also higher at Nag than at Coggeshall marsh in all zones, but this also declined significantly over time in the high marsh of both sites (Figure B-1).

Species richness, (i.e., the mean number of plant species recorded in each plot), was lowest in the low marsh, intermediate (averaging 3-4 species) in the high marsh and greatest in the upland edge where plots sometimes averaged over 5 species in both marshes. The upland marsh edge appeared to increase in species richness over time at Coggeshall marsh (significant Year by Zone interaction in Table B-1).

Non-living cover (primarily bare ground and dead plants) was similar between the two marshes and exhibited strong increases over time. The interaction term of Year by Zone was significant for non-living cover, which increased about 10% in low and high marsh over the sampling period, but not at the upper marsh edge (Figure B-1). Non-living cover appeared to decline at the upper edge of Coggeshall marsh as Sp+Ds+Jg cover appeared to increase. The variance from year to year was too great to be certain of these changes, but further monitoring over time may provide enough data to statistically support these trends.

Table B-1. Model results for univariate ANCOVA for *Narraganset Bay NERR* with two sentinel site marshes combined showing *p* values for Site, Zone and Year and their interactions as well as the overall *F* statistic and proportion of variance explained, R^2. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.

Dependent Variable	Transformation Data Excluded	n	Overall F	R2	MARSH SITE	MARSH ZONE	YEAR	Site X Zone	Year X Zone	Year X Site
Spartina alterniflora	LN	28	56	0.94	0.0001	0.0001	0.4183	0.0001	0.0356	0.9180
Spartina patens		42	295	0.99	0.0001	0.0001	0.0001	0.0001	0.0001	0.8478
SA : SP Ratio	LN; upland edge plots	28	828	0.99	0.0001	0.0001	0.0001	0.0001	0.0001	0.0825
Sp+Ds+ Jg	LN	42	258	0.99	0.0001	0.0001	0.0001	0.0001	0.0001	0.0244
Species Richness		42	39	0.92	0.8902	0.0001	0.5408	0.0224	0.0178	0.4415
Non-Living		42	5.7	0.62	0.2864	0.0035	0.0001	0.2775	0.0261	0.1516

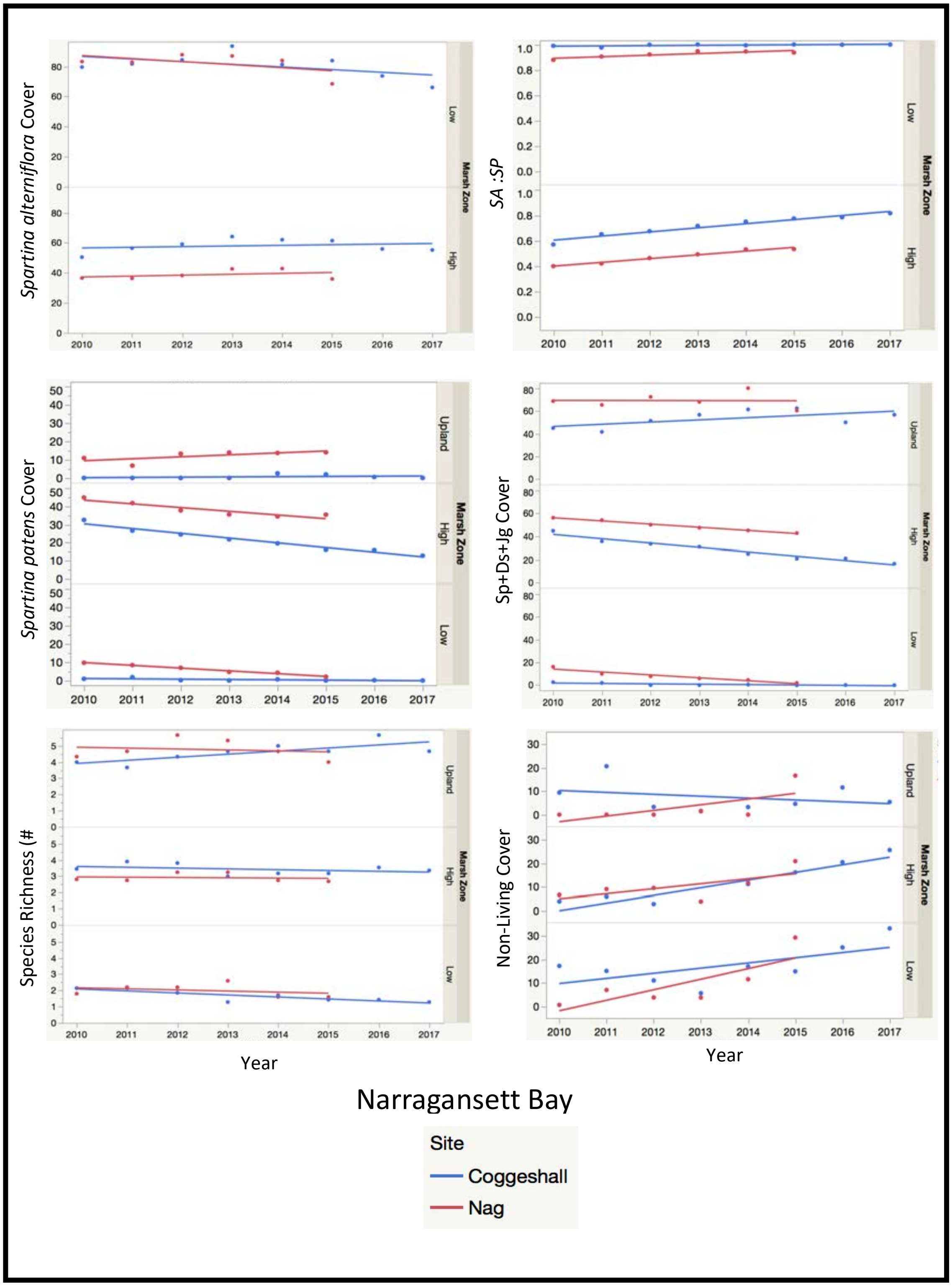


Figure B-1. Cover of selected species and other dependent variables from Narragansett Bay NERR analyzed in ANCOVA (Table B-1) showing change over time for each marsh Site and Zone. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.

Waquoit Bay NERR
The two marsh Sentinel Sites on Sage Lot Pond, a sub-embayment of Waquoit Bay, extend from the tidal pond to dune edge (south) and forest edge (north). Generally, the marsh leading into the dune had 15 to 20% greater S*. alterniflora* cover than the marsh leading to the forest. However, *S. alterniflora* cover declined in the dune edge marsh over time while the forest edge marsh declined more slowly or increased in the high marsh (Table B-2, significant Site by Year interaction) so that by 2017 the two areas had similar amounts of S. alterniflora: about 40% cover in the low marshes and 30-40% cover in the high marshes (Figure B-2). The results are similar to those found earlier by Warren and Niering (1993) in Connecticut where expansion of *S. alterniflora* was coupled with the loss of *S. patens*. No *S. patens* was found in the low marsh at either site, but declines were observed in the high marshes and upland edge zones. The cover of *S. patens* found in these high marshes (10 to 15%) was small relative to other New England marshes in this study, and by 2017, had declined to an average of only 5%. The SA:SP ratio increased significantly over time in the forest edge high marsh but not in the dune edge high marsh, showing that the forest edge marsh SA:SP ratio was approaching 1.0 and wholly dominated by *S. alterniflora* (Figure B-2). When we broaden our examination of the high marsh to include typical associates of *S. patens*, namely *D. spicata* and *J. gerardii*, we find the average cover of the sum of these three high marsh species declined in high marsh and upland edge zones (significant Zone by Year interaction) at similar rates in both marshes (Site by Year interaction not significant; Figure B-2).

Salt marsh forbs, a suite of herbaceous dicots, is a small component in salt marshes, but can be important in supporting plant and animal diversity (Ewanchuck and Bertness 2004). Forb cover averaged greater than 12% in the Forest edge but only 3% in the Dune edge high marsh in 2011 (Figure B-2). Through the sampling period, forb cover increased in the dune edge, but decreased in the Forest edge, so that by 2017 the two marsh sites supported similar amounts of forbs, averaging about 7% cover in the high marsh (significant Year by Site interaction; Table B-2). While sea level rise may lead to greater soil saturation in the high marsh and promote more forbs (Warren and Niering 1993), increased temperatures have been shown to increase perennial grasses and decrease forb cover (Gedan and Bertness 2009). Since these two sites lay on either side of a small tidal pond, large scale changes cannot account for changes in forb abundance. As such, they may result from subtle competitive differences between sites: *S. alterniflora* increased where forbs decreased and decreased where forb cover increased; Figure B-2).

Species richness was lowest in the low marsh (about 2 species per plot), intermediate (4-6 species) in the high marsh and greatest in the upland edge where plots sometimes averaged over 8 species. Despite significant interactions with Site, Zone and Year, there was not much change in species richness over the sampling period. Non-living cover was greatest in the low marshes in Sage Lot Pond, averaging 50 to 60% cover (the effect of Zone was significant; table B-2). Year was also significant, and it appears non-living cover increased in the high marsh from 20 to 30% over the sampling period (Figure B-2).

Table B-2. Model results for univariate ANCOVA for *Waquoit Bay NERR* with two of their sentinel site marshes combined (Sage Lot Dune Edge and Forest Edge) showing *p* values for Site, Zone and Year and their interactions as well as the overall *F* statistic and proportion of variance explained, R^2. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.

Dependent Variable	Transformation Data Excluded	n	Overall F	R2	MARSH SITE	MARSH ZONE	YEAR	Site X Zone	Year X Zone	Year X Site
Spartina alterniflora	upland edge plots	28	18.1	0.838	0.0001	0.0001	0.3421	0.0903	0.1247	0.0151
Spartina patens	LN	40	69	0.95	0.0001	0.0001	0.0001	0.0002	0.0068	0.2732
SA : SP Ratio	ArcSin; upland edge plots	28	83	0.96	0.0002	0.0001	0.0113	0.0074	0.0353	0.0212
Sp+Ds+Jg	SqRt*	40	148	0.98	0.0001	0.0001	0.0001	0.0098	0.0240	0.7097
Forbs	LN	40	23	0.87	0.0758	0.0001	0.1268	0.0085	0.8795	0.0194
Species Richness	LN	40	321	0.99	0.0001	0.0001	0.0016	0.0033	0.0414	0.0125
Non-Living		40	23.0	0.87	0.9268	0.0001	0.0155	0.0043	0.2114	0.7860
*distribution of residuals non-normal										

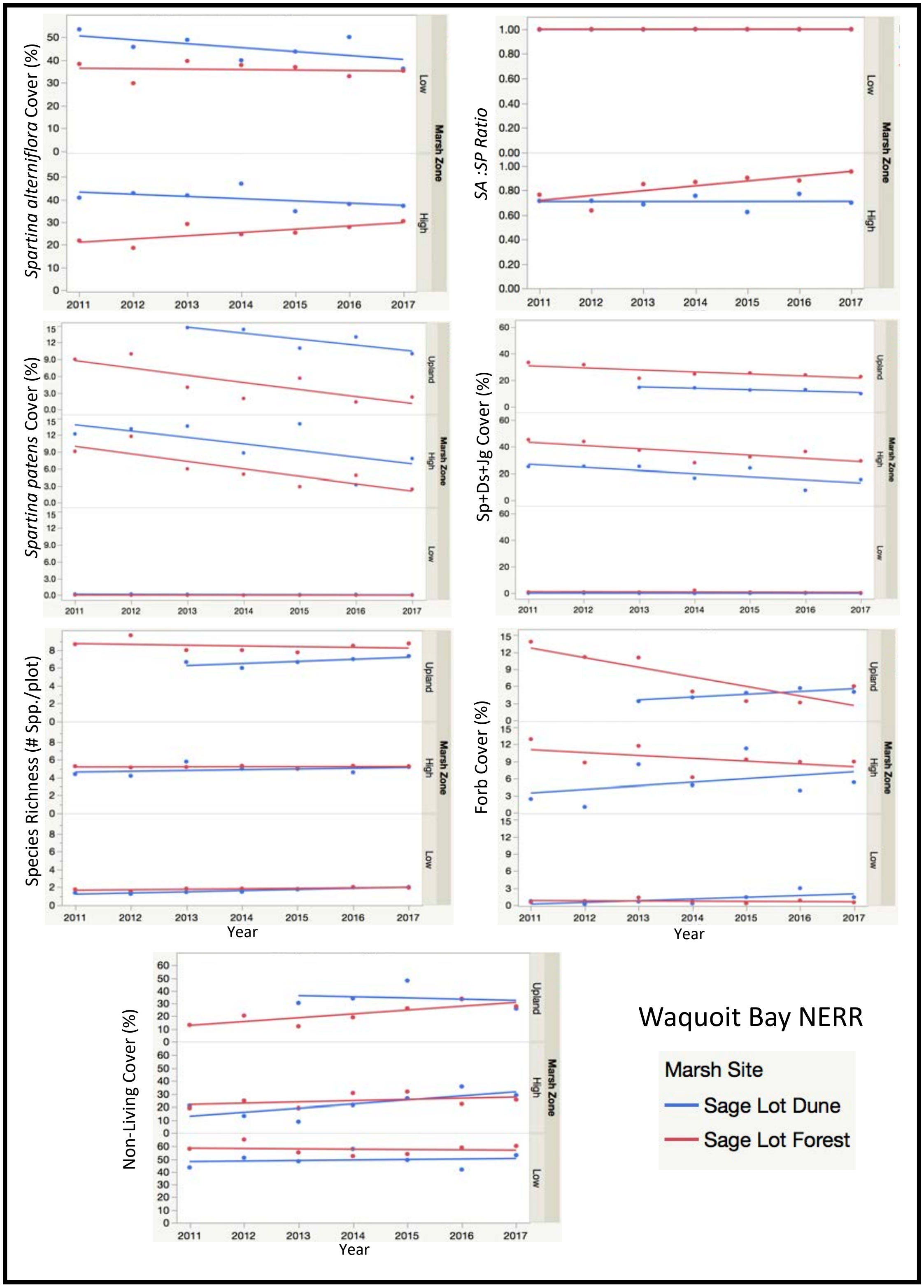


Figure B-2. Cover of selected species and other dependent variables from Waquoit Bay NERR analyzed in ANCOVA (Table B-2) showing change over time for each marsh Site and Zone. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.

Great Bay Estuary, Great Bay NERR

Three marshes were regularly sampled in the Great Bay NERR: Sandy Point which runs along the south shore of Great Bay, a small riverine marsh on the eastern shore called Great Bay Farms and Bunker Creek, another small riverine marsh that abuts the Oyster River (see Figure 4). The three marshes differed in character, with Bunker Creek dominated by low marsh, which is uncommon in New Hampshire. The three marshes were set up with two special plots on each transect between the low marsh and high marsh forming the transitional marsh zone.

When the plots were established, *S. alterniflora* averaged 50 to 70% cover in the low marsh, with the remainder being bare or dead plants (non-living). Over time a decline in *S. alterniflora* cover was consistent across the low marsh areas as well as increases in average cover within the transition plots but no change in high marsh plots (Figure B-3). At the same time, *S. patens* showed declines in transition zone plots in two of the three marshes, but Year and Year by Zone were not significant effects in the *S. patens* model (Table B-3). The SA:SP ratio did show a significant Year effect, with increases of *S. alterniflora* relative to *S. patens*. This similar to the changes documented in Massachusetts (Smith et al. 2009) and Rhode Island previously (Donnelly and Bertness 2001; Raposa et al. 2017, Watson et al. 2017b) and the transition zone highlights the changes observed at the other New England NERR marshes that do not have special transition plots.

The high marsh dominants represented by Sp+Ds+Jg varied by marsh and zone but cover was fairly consistent over time in the three marshes (Figure B-3). The cover of forb species in the high marsh varied by site (Great Bay Farms lowest), but changes over time were not significant with the model used. This may be due to high year-to-year variability for this group, which is composed of many annual species. Tracking changes in forb abundance over time may require a longer sampling interval and a focus on individual marshes since differences among the three marshes at GBNERR may translate more strongly to forbs than the perennial grasses.

Species richness increased from low marsh to upland edge, as flooding stress decreased. Overall, there appears to be a slow decline in species richness, which is most obvious for the upland edge of Bunker Creek and Sandy Point marshes (Figure B-3; significant Site by Zone interaction in Table B-1). At Sandy Point, which is located directly on Great Bay, species richness increased as *S. alterniflora* cover decreased in the low marsh, presumably due to increases in algae species in the low marsh. Non-living cover (primarily bare mud and dead plants) varied by marsh site and zone but showed no consistent rends over time. It was highest at the upland edge of riverine marshes, likely due to their steep edges and tree cover (Figure B-3)

Table B-3. Model results for univariate ANCOVA for *Narraganset Bay NERR* with two sentinel site marshes combined showing *p* values for Site, Zone and Year and their interactions as well as the overall *F* statistic and proportion of variance explained, R^2. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.

Dependent Variable	Transformation Data Excluded	n	Overall F	R2	MARSH SITE	MARSH ZONE	YEAR	Site X Zone	Year X Zone	Year X Site
Spartina alterniflora	LN*; upland edges	54	204	0.99	0.0001	0.0001	0.0020	0.0001	0.0003	0.3032
Spartina patens	ArcSin	72	56	0.95	0.0001	0.0001	0.0573	0.0001	0.6281	0.6210
SA : SP Ratio	ArcSin; upland edge plots	54	130	0.98	0.0001	0.0001	0.0005	0.0001	0.1552	0.1621
Sp+Ds+Jg	ArcSin	72	128	0.98	0.0001	0.0001	0.5903	0.0001	0.3495	0.7978
Forbs	LN	72	11.5	0.78	0.0002	0.0001	0.0989	0.0001	0.0779	0.1356
Species Richness		72	50	0.94	0.0001	0.0001	0.0003	0.0001	0.0038	0.9177
Non-Living		72	11.0	0.78	0.0013	0.0001	0.7411	0.0001	0.1640	0.0970
*distribution of residuals non-normal										

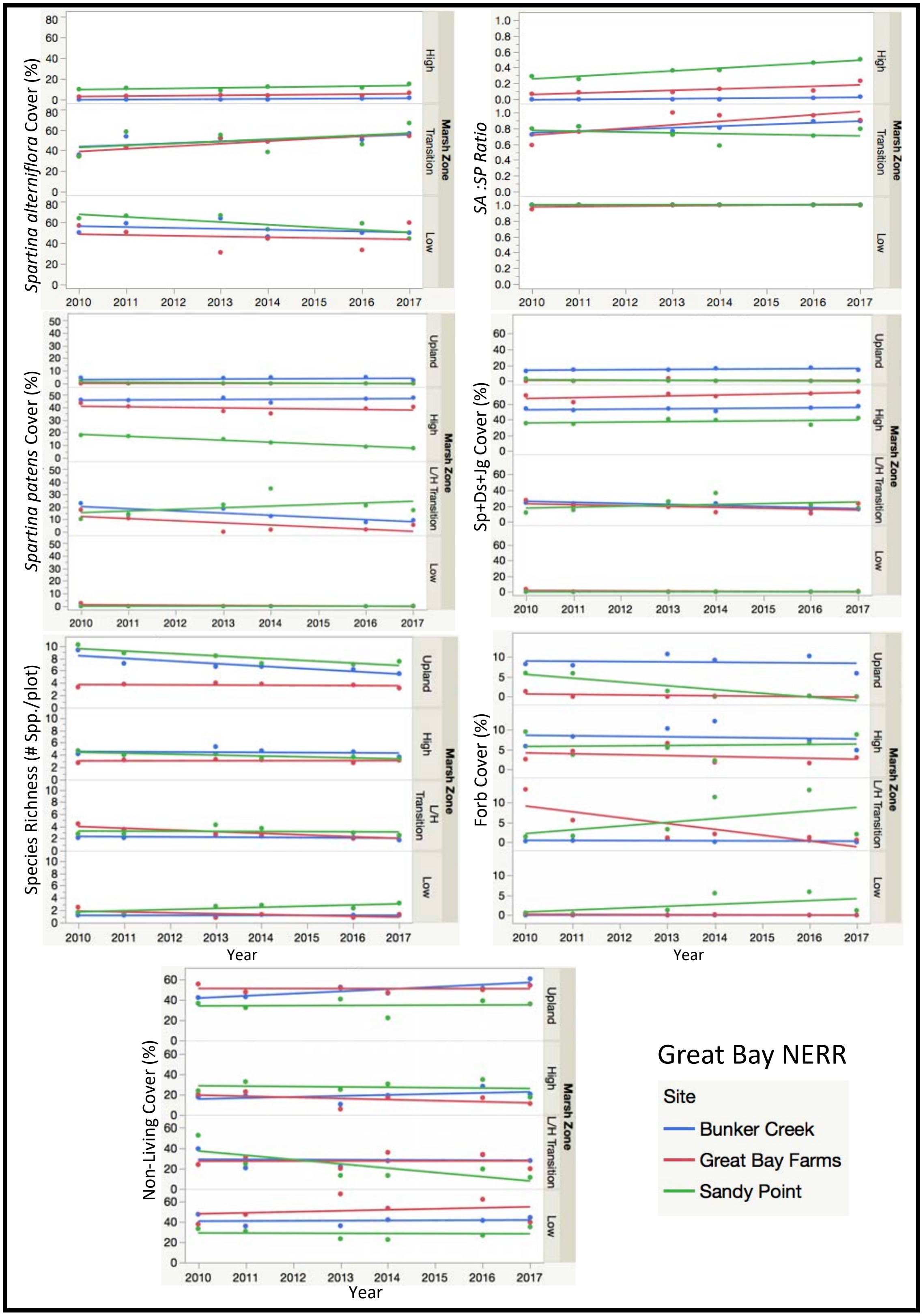


Figure B-3. Cover of selected species and other dependent variables from Great Bay NERR analyzed in ANCOVA (Table B-3) showing change over time for each marsh Site and Zone. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.

Webhannet Estuary, Wells NERR

The Webhannet River Estuary drains the most developed areas of Wells: the barrier beach, harbor complex, and US Route 1. The vegetation monitoring reported here continues a project which began in 2005 to examine potential impacts from climate change, sea level rise and development on the landward portion of the Webhannet Marsh (Dionne et al. 2007). Therefore, the Sentinel Site at Wells Maine was set up differently than the other New England Reserves, with four pairs of transects extending from the upland into, but not through, the marsh, typically terminating at a tidal creek. Each transect pair included one with and one without development in the adjacent upland. Since no statistical differences were found between transect types (developed *versus* undeveloped) and the amount of data was limited, the data from all eight transects were combined and used for the univariate analyses. The Wells Reserve established one Sentinel Site, so the univariate model has only Marsh Zone, Year and their interaction as independent variables (Table B-4).

Spartina alterniflora was found to have greater cover in the low marsh than in the high marsh and though it appeared to be increasing (Figure B-4), the effect of Year was not significant. *S. patens* also appeared to be decreasing in the low and high marsh, but year-to-year variation resulted in a non-significant effect. However, the ratio of *S. alterniflora* to *S. patens* cover did have a significant year effect, showing displacement of *S. patens* by *S. alterniflora* in the low and high marshes (Figure B-4) as we have seen for the other New England NERR Sentinel Sites. The sum of high marsh grasses (*S. patens, Distichlis spicata,* and *Juncus gerardii*) showed similar results to that of *S. patens*, but with greater representation in the upland edge (Figure B-4).

Forb cover was too variable to show change over time but did appear to be decreasing in the high marsh and increasing in the upland edge; further collections through time will determine whether this change is substantiated. Species richness per plot increased from low marsh to the upland, as in other Reserves, and temporal changes appear to be similar to those observed in the forbs, with no significant trends over time detected (Figure B-4). Non-living cover was generally highest in the low marsh, but year-to-year variability was high, resulting in no significant change over time (Year was not significant in Table B-4).

Table B-4. Model results for univariate ANCOVA for Webhannet Estuary, Wells NERR with two sentinel site marshes combined showing *p* values for Site, Zone and Year and their interactions as well as the overall *F* statistic and proportion of variance explained, R^2. Sp+Ds+Jg = *Spartina patens, Distichlis spicata*, and *Juncus gerardii* combined.

Dependent Variable	Transformation Data Excluded	n	Overall F	R2	MARSH ZONE	YEAR	Year X Zone
Spartina alterniflora	upland edge plots	10	11.3	0.85	0.0014	0.1403	0.8423
Spartina patens		15	10.8	0.86	0.0003	0.0587	0.2196
SA : SP Ratio	ArcSin; upland edge plots	10	43	0.96	0.0001	0.0100	0.3899
Dispi + Juger + Sppat		15	13.5	0.88	0.0001	0.2224	0.1278
Forbs		15	5.1	0.74	0.0108	0.0967	0.0895
Species Richness		15	4.9	0.73	0.0046	0.6833	0.2088
Non-Living		15	3.1	0.63	0.0137	0.5970	0.6682

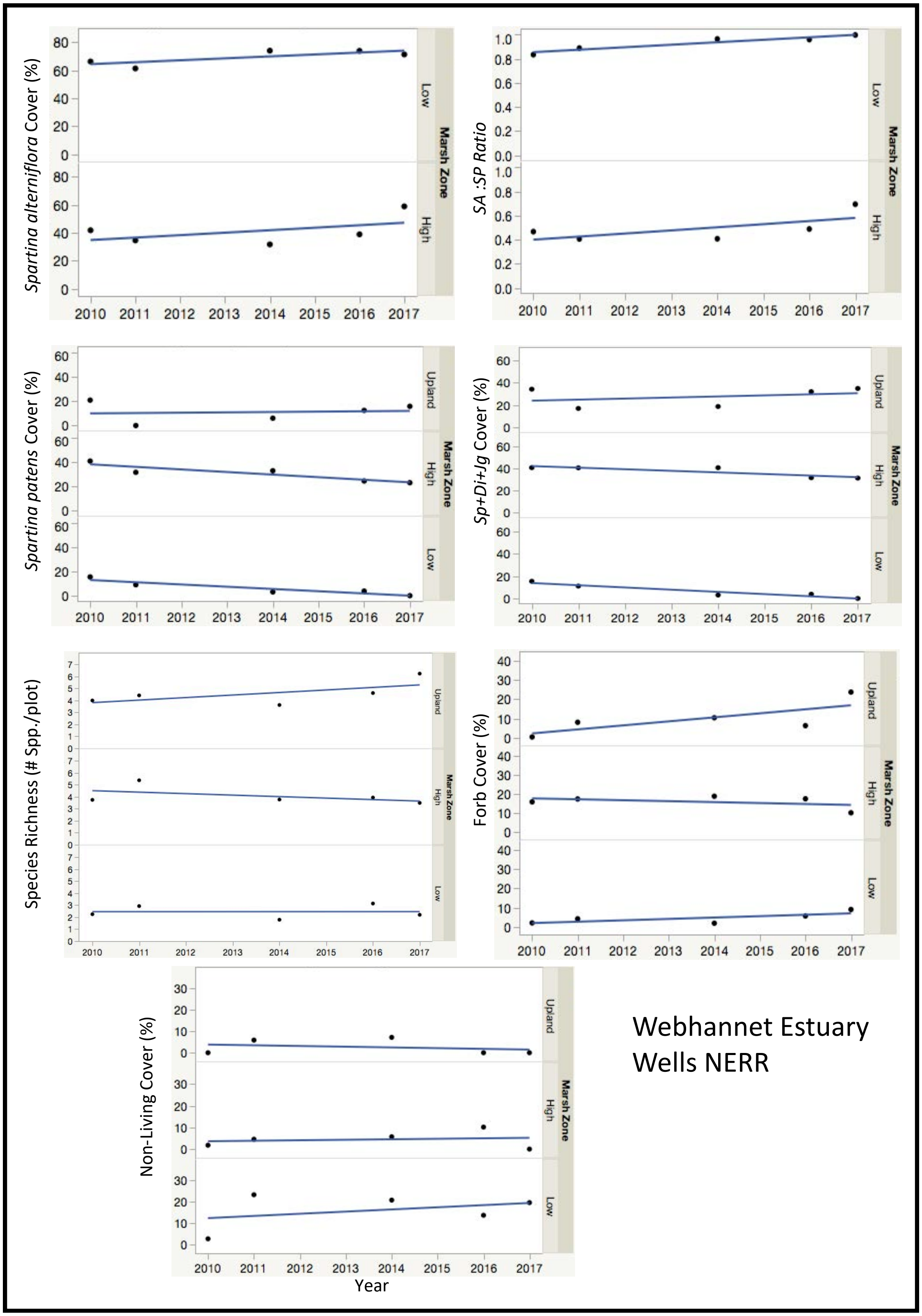


Figure B-4. Cover of selected species and other dependent variables from Webhannet Estuary, Wells NERR analyzed in ANCOVA (Table B-4) showing change over time for each marsh Zone. Sp+Ds+Jg is the sum of *S. patens*, *D. spicata* and *J. gerardii* cover.