NAMASTE: National-Level Analysis Methods and Results

NAMASTE
National Marsh Synthesis Team

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2025

This report was produced by the National Marsh Synthesis Team as part of a NERRs Science Collaborative.

For more details see our website:
www.nerra.org/impact/science/marsh-response-to-sea-level-rise/

Suggested Citation: Peter, C.R., J.G. McKown, K. Cressman, A.G. Yeates, D.M. Burdick, C. Fuert, K. McGovern, B. Russell, S. Shull, M. Tyrell, and L.E. White. 2025. NAMASTE National-Level Analysis Methods and Results. NERRs Science Collaborative Technical Report. 48 pp.

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Acknowledgements

This report would not be possible without the submitted data from all participating National Estuarine Research Reserves including ACE Basin, Apalachicola, Chesapeake Bay Maryland, Chesapeake Bay Virginia, Delaware, Elkhorn Slough, Grand Bay, Great Bay, Guana Tolomato Matanzas, Hudson River, Jacques Cousteau, Kachemak Bay, Mission Aransas, Narragansett Bay, North Carolina, North Inlet-Winyah Bay, Padilla Bay, South Slough, Tijuana River, Waquoit Bay, and Wells. Members of our Technical Advisory Group (TAG) provided invaluable feedback, including Adrienne Pappal (MA CZM), Ali Helms (South Slough NERR), Brandon Pucket (North Carolina NERR), Chris Kinkade (NOAA OCM), Christina Witeman (Delaware NERR), Mollie Yacano (Delaware NERR), Cristina Kennedy (MA DER), Ellen Cheng (NPS), Erik Smith (North Inlet-Winyah Bay NERR), Greg Hood (Skagit River Systems Cooperative), Greg Steyer (USGS), Jacob Aman (Wells NERR), Lauren Sutton (Kachemak Bay NERR), Jamie Vaudrey (CT NERR), Jason Goldstein (Wells NERR), Jenni Schmitt (South Slough NERR), John Callaway (USF), Katie Swanson (Mission-Aransas NERR), Kerstin Wasson (Elkhorn Slough NERR), Kyle Derby (Chesapeake Bay MD NERR), Laura Crane (Wells NERR), Megan Lamb (Apalachicola NERR), Melissa Ide (CDMO), Mike Archer (Grand Bay NERR), Miranda Madrid (Mission-Aransas NERR), Neil Ganju (USGS), Nikki Dix (Guana Tolomato Matanzas NERR), Nina Garfield (NOAA OCM), Patricia Delgado (Chesapeake Bay MD NERR), Randy Chambers (College of William and Mary), Robert Dunn (North Inlet-Winyah Bay NERR), Sarah Fernald (Hudson NERR), Scott Lerberg (Chesapeake Bay VA NERR), Shimi Rii (H’eia NERR), Susan Adamowicz (USFWS NWF), Sylvia Yang (Padilla Bay NERR), Tracy Buck (NIW NERR, CDMO), Jennifer Debose (Grand Bay NERR), Kenny Raposa (Narragansett Bay NERR), Christina Pacella (Hudson NERR), and Chris Mitchell (Hudson NERR). Members of the NERRs vegetation marsh working group were critical to the tidal marsh biomonitoring methods analyzed in this report. The NERRs Central Data Management Office (CDMO) is graciously hosting data compiled through this project. Funding was provided by the NERRs Science Collaborative.

Table of Contents

Introduction

The goal of this document is to provide a detailed data analysis of National Estuarine Research Reserve (NERR) data, including methods and results, to evaluate climate change impacts (primarily sea-level-rise) on tidal marsh plant communities at the broader **regional and national scale**. Following thorough data QA/QC (quality assurance and quality control), vegetation changes were documented using data summaries, visualizations, and statistical analyses.

Research Questions

1. Are plant communities shifting over time and do these differ across regions?
2. Are plant community changes accelerated or more prominent where local sea level rise (SLR) is proportionately greater relative to tidal range?
3. Are marshes that are failing to keep up with SLR (as ascertained by sediment elevation table (SET) data) showing the largest changes in vegetation?
4. Are there predictable, climate change-related geographic shifts in plant abundance and diversity?

Resources: Relevant documents are linked in the Resources section at the end of this document.

Background

Here, we conducted in-depth research utilizing nationally coordinated datasets collected using the NERR national tidal marsh vegetation monitoring protocol (Moore 2013; NERR 2025) to examine how plant communities in tidal marshes are responding to climate change. We used two broad groups of analytical techniques to accomplish this:

1. Univariate
    a. Summary Analyses
    b. LME Model Selection
2. Multivariate community ordination

Previous research on marsh change in response to sea level rise has been limited to local areas or regions, or meta-analyses (Burdick et al. 2020, Thorne et al. 2018; Osland et al. 2019). Here, we help to better quantify and describe changes occurring system-wide throughout the National Estuarine Research Reserve's (NERR) tidal marshes, incorporating data visualizations and analyses that can inform a wide variety of audiences. Synthesizing vegetation data at a national scale is important for identifying hotspots of vegetation loss or change; this focused effort will be one of the first steps to guide tidal marsh management strategies or system-wide climate change mitigation efforts. To understand tidal marsh change over time, we designed statistical tests, figures and tables to answer the following questions:

What is changing?

- Dependent variables such as total live cover, plant diversity, etc

When are they changing?

- Select time periods

Where is this change?

- High level (nation, region, reserve)
- Site attributes (geomorphology, tidal range, salinity)
- Plot attributes (vegetation zone, distance to water)

Why are marshes changing?

- Driving factors (Metonic cycle, climate, sea level rise, marsh elevation change)

Relevant Definitions

Reserve - National Estuarine Research Reserve (NERR), where one or more sites are monitored

Site - cluster of plots designated by Reserve practitioners as unique sites based on marsh units

Plot- specific area of marsh where a quadrat is repeatedly used to measure the plant community, typically $1m^2$

Zone - vegetative sub-communities within a marsh, described by vegetation species and elevation (e.g., low marsh, high marsh, upland edge) present at the time of plot establishment

Ecotone Migration Index (EMI)- ratio of Reserve-identified indicator covers of SLR (biotic or abiotic) to total cover. Indicator covers are selected by zone or 'ecotone' for each Reserve, (i.e., *Spartina alterniflora* as an indicator cover in the high marsh at Great Bay Reserve, New Hampshire)

Sediment Elevation Table (SET)- instruments used for precise measurements of marsh surface height over time to track the natural changes in marsh elevation that occur through plant root growth and sediment deposition

Technical Advisory Group (TAG)- larger group of 50 external advisors with experience in tidal marsh ecology, data collection, management, and/or analysis from around the country (NERR staff and external partners), tasked with advising on project methods

Technical Working Group (TWG)- smaller group of 10 project team members with extensive experience in tidal marsh ecology and/or statistics, tasked with analyzing the data

Process

Our overall process to draft a national analysis plan involved (1) building off the Reserve-Level Analysis Methods and Results, (2) utilizing our project team expertise in the TWG (Technical Working Group) and TAG (Technical Advisory Group), and (3) learning from similar efforts by looking through the literature and working with project teams with parallel goals (e.g., national synthesis of other datasets, tidal marsh work at smaller scales [New England vegetation synthesis]).

(1) **Review prior work**- Built off the Reserve-level analysis, our team reviewed all results and highlighted key findings, then scaled up appropriate visualizations and analyses to the national level when appropriate.

(2) **Advisory committees**- Our team conducted several monthly TWG meetings focused on discussing the goals, analyses, and data structure (data frames). A sub-working group with expertise in analyzing ecological datasets met in addition to the TWG to help refine

those aforementioned components of the plan. Finally, we presented a draft to the larger TAG to gain additional feedback to help inform the final plan.

(3) **External collaboration**- Project PIs and team members were also involved in many other NERR projects that have overlapping processes and/or goals including SWMP synthesis, SWMP catalyst, National Assessment of Marsh Decomposition (i.e., Tea-time), New England Vegetation Synthesis, and SAV (Submerged Aquatic Vegetation) workgroup. Our project team also reviewed literature that is relevant to drafting our analysis plan.

Data frames

Data for all Reserve files were compiled into one dataset for the national analyses, and aggregated at different levels to enable any or all of plot-level, vegetation zone-level, or site-level groupings. A data frame structure was created through reviewing our Reserve dataset templates, national metadata (via data matrices and Arc dashboard), and input from the TWG. Our data frame includes data we compiled and generated from NERR data (Moore 2013; NERR 2025) as well as external data (e.g., tides, weather). A data dictionary fully describes our national data with a sheet for each national data frame (Table 1).

Table 1: Dataframes used to analyze marsh trends, comprised of data directly from the Reserves and external data.

Data frame files	**Description**
national_plot-level	Combined file with one row per vegetation plot per date, where columns represented vegetation groups or categories and other metrics of interest (e.g., species richness, EMI). Sites identified for exclusion from national analyses (due to e.g., not having a minimum number of plots, or being a restoration site) are not included in this file.
veg_and_expl	National plot-level file, combined with information from the explanatory matrix (see below). Excluded sites not included in this file.
slopesAndExpl_byPlot	Estimates of change through time for each metric of interest, calculated for each vegetation plot via simple linear regression (metric ~ year).
slopesAndExpl_bySite	Plot-level estimates of change through time, averaged to the site level.
slopesAndExpl_byZone	Plot-level estimates of change through time, averaged to the vegetation zone (within site) level. Vegetation zone was lumped to 'low', 'mid', and 'up' from 11 possible categories earlier in data processing.
Reserve-level data	files ending with "_veg.xlsx" specified for each Reserve including vegetation cover data for each Reserve
Reserve-level analysis specs	files ending with "_veg-specs.xlsx" specified for each Reserve that includes species identified for Ecotone migration index for each Reserve.
Explanatory matrix	Spreadsheet of compiled information about each Reserve and/or site. To view compiled and generated metrics, see the data dictionary ('veg_and_expl' tab, rows 44-80).

Code to compile the national data frames can be found in Kim Cressman's github repository (swmpkim/nmst-national). Processing steps are as follows:

1. ***Pre-processing Reserve files:*** *01_pre-processing.R.* For each Reserve, data and 'spec' files were read into R and the following procedures were conducted. This had to be run at the Reserve level to take into account specific species and ecotone migrators at each Reserve, and so a .csv was generated for each Reserve.
    a. Check explanatory matrix to see if Reserve uses PI (point intercept) or OC (ocular cover) methodology for cover data. If PI, then convert to OC based on coefficient values in the PI-to-OC tab of the explanatory matrix.
    b. Force all rows' cover readings to total 100.
    c. Calculate EMI for each plot on each date, based on the "Ecotone_Invaders" tab of the Reserve spec file.
    d. Calculate species richness and Shannon-Weiner diversity, both for species or categories identified as "Live vegetation" in the "Species_Names" tab of each Reserve's data file, for each plot on each date. The 'vegan' package was used for these calculations.

    e. Calculate cover by species or cover group (e.g., A-Algae, B-Brackish, H-Halophyte; Bare, Dead) by summing cover by species for each category, based on categorizations in the “Species_Names” tab of the Reserve data files. Species groups were used rather than individual species because individual species are so different at a national scale that single species comparisons would be impossible.
    f. Calculate additional covers or ratios as determined by the TWG; e.g., non-native invasives; Salt-to-Total live vegetation ratio (Salt = plants labelled as Algae, Brackish, or Halophyte; when total live was 0, ratio was set to NA); Unvegetated-to-live vegetated ratio
    g. Certain individual species of regional interest were also retained for potential future analyses: *Spartina alterniflora*, *Juncus roemerianus*, *Spartina patens*, *Salicornia pacifica*.
    h. Attach the Reserve-defined vegetation zone to each plot, along with latitude, longitude, orthometric height, and distance to water; all as defined in the “Station_Table” sheet of the Reserve data file.
    i. Save a .csv of the grouped data frame for use in the next steps.
2. ***Combining data across Reserves:*** *02_combining.R.* The grouped data from each Reserve, from step 1 above, was read and all data frames combined into a single data frame, with all readings from all vegetation plots on all dates. Sites identified for exclusion in the screening matrix (see Site Screening Process section below and the explanatory matrix [described with the data dictionary above]) were removed before combination of data. The combined file was written out as *national_plot-level.csv*. A later version was created that did not exclude any sites, for generation of graphics for the dashboard. This later version is *national_plot-level_AllSites.csv*.
3. ***Combining plot-level data with explanatory variables:*** *03_explanatory_matrix.R.* The national, plot-level data frame from step 2 was combined with additional explanatory factors, resulting in the *veg_and_expl.csv* file.
    a. Information from the “Time added” and “Time removed” sheets of the explanatory matrix was bound to the national plot-level csv from above, by Reserve and Site.
        i. “time added”: annual averages for the growing season (Apr-Sep) of temperature, precipitation and water levels
        ii. “time removed”: site level characteristics and overall rates of change (e.g., salinity, geomorphology, sea-level-rise rates from nearest tide stations, SETs, metrics from other projects, etc.)
    b. Vegetation Zones were lumped: in Reserve-level data, there were 11 zone options. For easier comparison at the national scale, these were combined into:
        i. Low: Mudflat, Seaward Edge, Low Marsh, Pools/Pannes
        ii. Mid: Transition, High Marsh
        iii. Up: Upland Edge, Freshwater Tidal, Upland
4. ***Calculation of change at various aggregation levels:*** *04_national_slope_df_construction.R.* The plot-level vegetation + explanatory factor file was used to generate estimates of change-through-time for each metric of interest at

the plot scale, then averaged to zone-within-site and site. Three files were generated, one for each level of aggregation.

a. Estimates of change-through-time for each metric of interest (vegetation groups, EMI, and ratios generated in step 1; additionally on some explanatory factors such as average temperature and sum of precipitation) were calculated using simple linear regression at the level of the individual vegetation plot. The output file is *slopesAndExpl_byPlot.csv.*
b. Slopes for each plot were averaged to the level of site. The output file is *slopesAndExpl_bySite.csv.*
c. Slopes for each plot were also averaged to the level of vegetation zone within the site. The output file is *slopesAndExpl_byZone.csv.* The site averages do not take vegetation zone into account.

Site Screening Process

A number of sites were excluded from the national analysis per the screening matrix (Figure 1) to ensure our dataset best addressed our research objectives, which focused on tidal marsh change at relatively undisturbed sites. Specifically, our finalized national input data <u>excluded</u>:

- Data
    - ≤ 3 years of data per site, spanning 5 years or more
    - <15 plots per site
- Sites
    - Atypical- freshwater, restored, and heavily impacted sites
    - Methods were non-compliant:
        - Excluded sites with where transects were not-perpendicular across multiple zones
        - Excluded sites where the monitoring method for cover was uniquely different from national protocol
    - Data omission/errors
        - Sites mistakenly excluded from our national analysis results
            - CBV Goodwin Island
            - GTM 06 Moses Creek
            - SOS Fredrickson
            - SOS Winchester Marsh
        - Sites mistakenly included in our national analysis results
            - WQB Section 3 - tidally restricted
            - CBM OPC - tidal fresh
            - TJR Brazo - minimum plot #

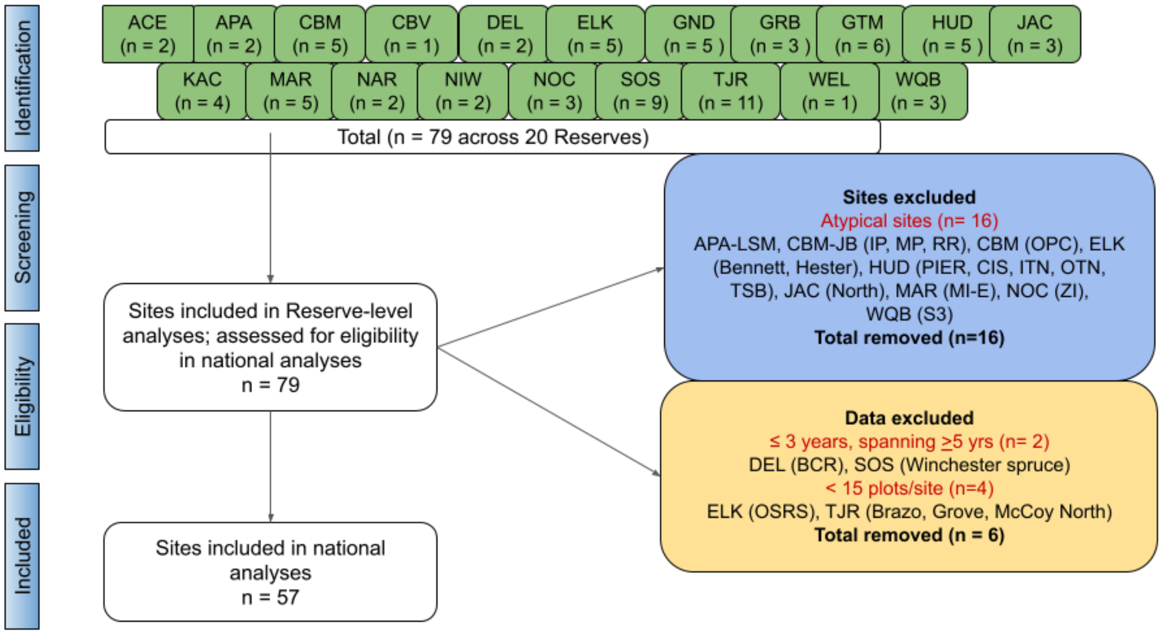


Figure 1: Screening matrix for the national level analysis plan that included 56 sites.

Variables and Tests

Dependent variables

Below is a summary of dependent variables used in this plan. For the full and updated list, see our data dictionary. Italicized parameters below were generated specifically for this project.

- **Abiotic categories**: Total, Abiotic, Bare, Dead, Other Unvegetated, Rock, Wood, Wrack, Overstory, Water
- **Plant categories**: *Total Live Veg, Algae, Brackish, Freshwater, Halophyte, Upland, Other live vegetation*
- **Metrics and ratios**: *EMI (ecosystem migration index), Richness, Diversity, Invasives (total), Salt:Total ratio, Total Unvegetated*
- **Species**: Juncus roemerianus, Spartina alterniflora, Spartina patens, Salicornia pacifica

Independent variables

Below is a summary of independent variables used in this plan. For the full and updated list, see our data dictionary. Italicized parameters below were generated specifically for this project.

- Site level (time removed)
  - *Geomorphology, Tidal Range, Salinity category, SLR rate (period-of-record, since 1970, recent 19 yr), SET rate of change*, Latitude, Region
  - NERR projects:
    - MARS (Marsh Resilience to Sea Level Rise) (Raposa et al. 2016)
    - NERRs Landscape (Stevens et al. 2023)
      - resiliency condition sum

            - resiliency vulnerability sum
            - Unvegetated:Vegetated Edge ratio
            - Core:edge ratio
            - % Natural
            - tidal range
            - NERRs Landscape % MUC (marsh unit code) below MHHW (mean high high water)
- Site level (time retained to year)
    - *Local tidal range, Climate - temp, Climate - precip*
- Plot level: *Vegetation zone, Distance to water*
    - Random effects: Site, Transect, Plot
    - For vegetation zone, there are 11 categories with many that are more relevant locally or regionally. To facilitate easier comparison nationally, zones have been grouped into these broader categories:
        - Low = M-Mudflat, S-Seaward Edge, L-Low Marsh, P-Pools/Pannes
        - Mid = T-Transition, H-High Marsh
        - Up = UE-Upland Edge, DB-Dunes and Berms, FT-Freshwater Tidal, FN-Freshwater, U-Upland

Tests

- Reserve-level analyses scaled up to national level
    - Summary charts
    - Univariate modeling
    - Multivariate modeling
- Additional models
    - Linear Mixed Effects Models (LME)

Methods: Univariate - Summary Analysis

Here, we break down this section into three different approaches to (1) detect significant changes in the vegetation community, (2) visualize change in the vegetation community, and (3) identify possible explanations for observed trends. For the simple univariate models, we used a systematic approach to investigate changes across time in tidal marshes at a national level by utilizing a comprehensive and exploratory strategy that includes a robust but prioritized list of dependent and independent factors to learn more about:

What?	Which dependent variables are best capturing change?
Where?	In what part of the country (region, reserve), what type of estuaries (site-level: tide range, salinity, etc), and where in the marsh (plot-level: zone, distance to water) is change occuring?
When?	Are changes linear or nonlinear?
Why?	What are the driving factors of change?

Associated Resources

- R Project on McKown GitHub

Data Analysis Outline

Correlation Analysis:

- Understand possible correlations between selected vegetation metrics

Site-level Regressions & Compilation Analysis:

- A secondary lens of viewing change in the vegetation community nationally, regionally, and by site characteristics
- Simple linear models were conducted and p-values and slopes summarized; EMI was compiled differently due to the universal directional meaning of the metric

National Mixed Linear Regressions

- Mixed linear regressions over time were conducted on site-level summarized vegetation data to better understand how vegetation metrics changed over time and if change was impacted by site characteristics of vegetation zone

Explanatory Factor Regressions:

- Simple linear regressions were conducted with site-level rates of change (slope estimates from national data frame compilation) of vegetation metrics versus Sea Level Rise and NERRS Landscape Condition Metric

Data Analysis Factors

Vegetation Metrics

- Live Cover
- Abiotic Cover
- Halophyte Cover
- Freshwater Cover
- Ecotone Migration Index
- Salt Ratio
- Species Richness
- Shannon - Weiner Diversity

Site Characteristics

- Region (Northeast, Mid-Atlantic, Southeast, Gulf Coast, West Coast)
- Geomorphology (Bay Front, Back Barrier, Riverine)
- Salinity Regime (Oligohaline, Mesohaline, Polyhaline)
- Tidal Range (Microtidal, Mesotidal, Macrotidal)
- Vegetation Zone (Low, Mid, Up)

Explanatory Factors

- Sea Level Rise (Last 19 Years)
- NERRS Landscape Condition Metric

Data Preparation

The only alteration made to the national plot data frame was transforming all NA values for the vegetation metrics to zeroes. For instance, it can be implied that if the Halophyte Cover value of a measured plot is NA, it should be zero since no halophyte species were recorded. Plot data was then averaged across (1) Site and (2) Vegetation Zone within each Site.

Spearman Rank Correlations

First, Spearman Rank correlations were conducted between selected vegetation metrics to better understand if vegetation metrics were correlated with each other. Spearman Rank correlations were used, as opposed to Pearson Correlations, as we were more concerned about directional change between metrics rather than a linear relationship. The r and p-values of the correlations were extracted from the models for review and visualized (Figure 2). Spearman-rank correlations were completed and visualized with 'Himsc' and 'GGally' R packages.

Experimental Unit: Site
Analysis: Spearman correlation

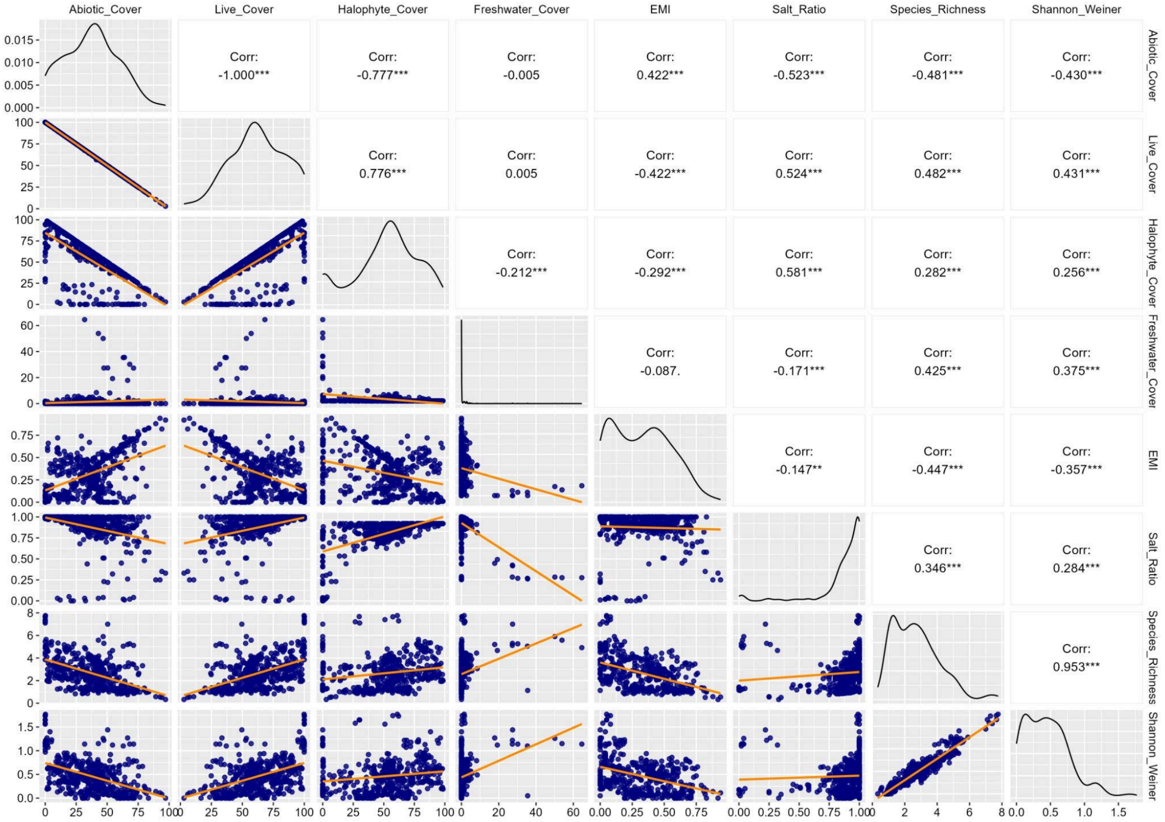


Figure 2: Spearman rank correlation matrix of the selected vegetation metrics at the site level with Spearman Rank r and p-values in the top half, distribution of data between paired metrics bottom half, and the distribution of the data for each vegetation metric in the middle diagonal.

Site-level Regressions and Compilation Analysis

Second, a compilation analysis was conducted as a complement to the national regressions. The goal of the compilation analysis was to (1) Calculate mean +/- standard error of slopes of site-level regressions nationally and across site characteristics and (2) Quantify the percentage of sites nationally and across site characteristics with significant trends. For goal 1, simple linear regressions were conducted for each site of each vegetation metric. Slopes were extracted from the 'estimate' of the linear models. Mean +/- standard errors were calculated for slopes nationally and for each site characteristic (Figure 3). For goal 2, a different approach was taken to account for whether vegetation community change was across the whole site or localized within a given vegetation zone. For sites with two or more vegetation zones, an ANCOVA was conducted with Year, Vegetation Zone, and their Interaction as fixed factors for each site. For sites with only one zone, a simple linear regression of just Year as a fixed factor was conducted. Sites with a significant p-value in the Year or Interaction term were counted as a site with a significant trend in a given vegetation metric. The percentage of sites with significant trends were calculated nationally and for each site characteristic (Figure 4).

For the Ecotone Migration Index, however, a unique approach was developed to calculate a "score" that incorporated the magnitude of the p-value and the direction of the slope, since the EMI is unidirectionally (i.e., increasing trends indicate effects from SLR). Scores for each site were as follows: p-value < 0.05 = 2, 0.05 < p-value < 0.20 = 1.0, p-value > 0.20 = 0. Slope direction determined if the score was positive or negative (Figure 5).

Experimental Unit: Plot
Analysis: Simple linear regressions
Regression Equation in R:

1. Vegetation Metric ~ Year
2. Vegetation Metric ~ Year * Vegetation Zone

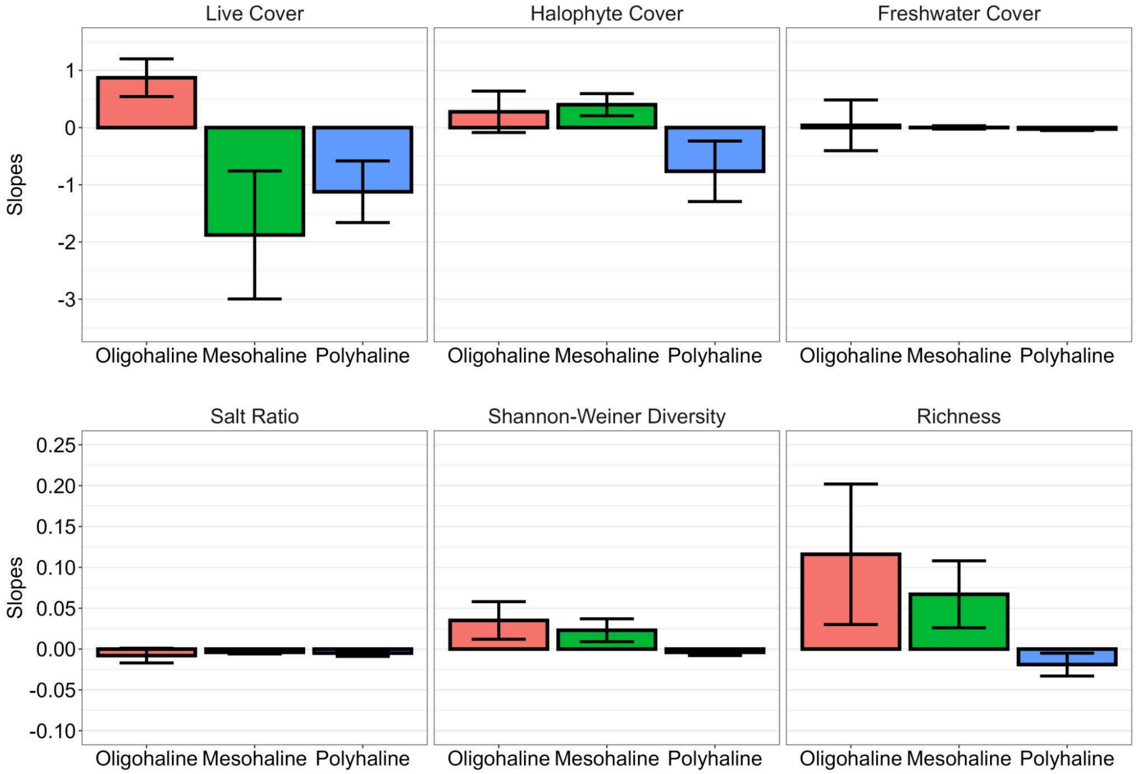


Figure 3: Summary of mean +/- standard error of slopes from site-level regressions (exp. unit = plot) for selected vegetation metrics across salinity regimes.

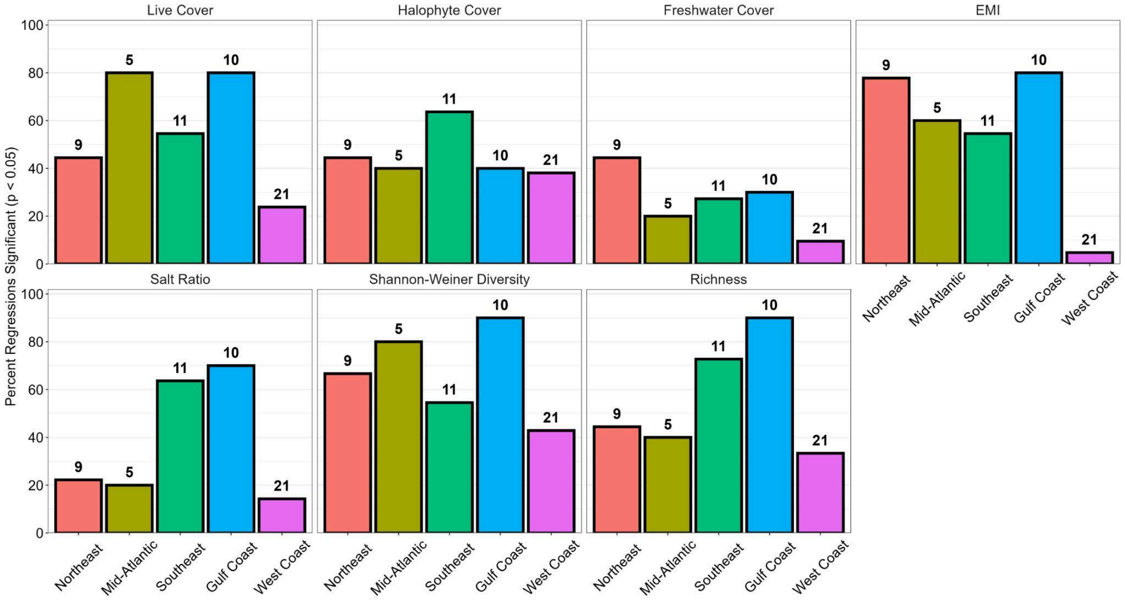
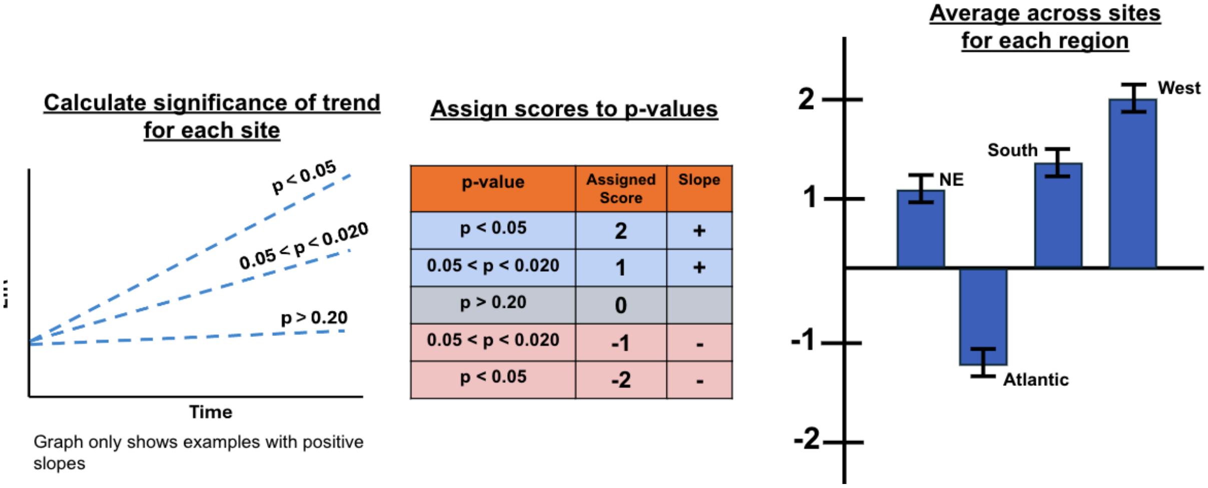


Figure 4: Summary of percentage of sites with a significant trend (Year or Interaction with Vegetation Zone) from site-level regressions (exp. unit = plot) for each vegetation metric in each region.



p-value	Assigned Score	Slope
p < 0.05	2	+
0.05 < p < 0.020	1	+
p > 0.20	0	
0.05 < p < 0.020	-1	-
p < 0.05	-2	-

Figure 5: Scoring guidelines for the compilation analysis of Ecotone Migration Index from site-level regressions (exp. unit = plot).

National Mixed Linear Regressions

Third, mixed linear regressions were conducted across time at the vegetation zone or site-level to detect changes in vegetation metrics at a national geographic scale. Mixed linear models included Vegetation Zone or Site Characteristics, Time, and their interaction as fixed factors and Site nested within Region as random factors (Figure 6). If Year or the Interaction term were significant, slopes were calculated for each model by predicting the values of the model with 'ggpredict' package. Predicted values were calculated with only consideration of the fixed effects and error was estimated as a confidence interval. Regressions were visualized primarily with standard error. In a few instances where standard errors spanned most of the data range due to high variability of parameters (e.g., Shannon-Weiner diversity), graphs were visualized with 95% confidence intervals to facilitate ease of data interpretation within graphs (Figure 7). Linear mixed models were completed with the ‘lme4’, ‘purrr’, and ‘broom.mixed’ R packages.

Experimental Unit:

1. Site
2. Vegetation Zone within Site

Analysis: Mixed Linear Regressions

Regression Equation in R:

1. Vegetation Metric ~ Year * Vegetation Zone + (1 / Reserve(Site))
2. Vegetation Metric ~ Year * Site Characteristic + (1 / Reserve(Site))

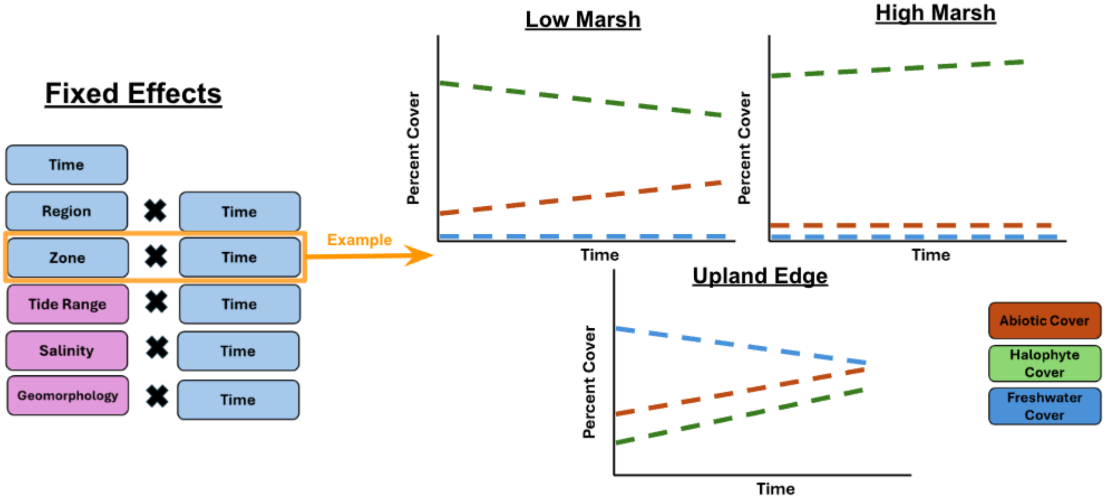


Figure 6: Overview of the fixed factors and mixed linear modeling at the national level (exp. unit = site).

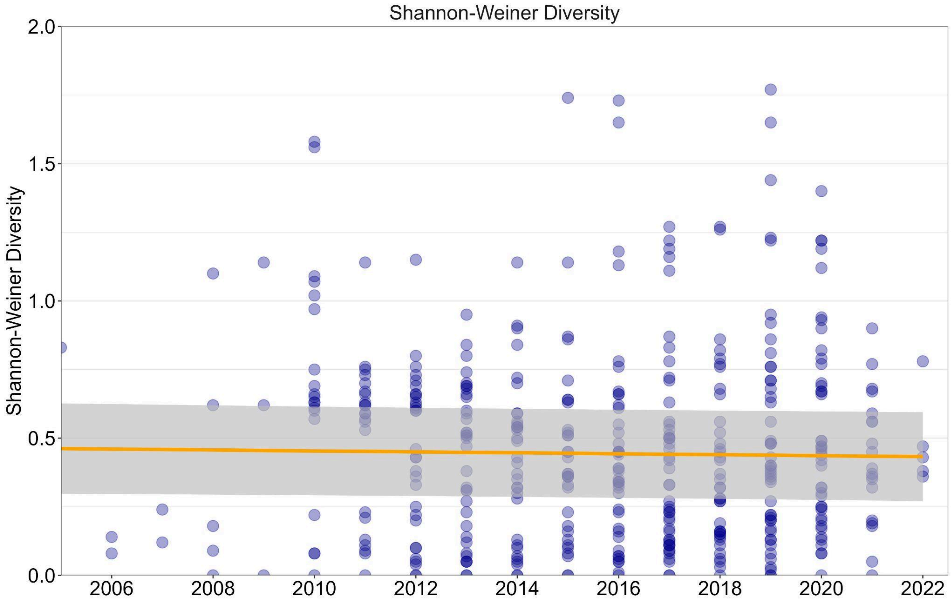


Figure 7: National linear mixed model (exp. unit = site) of Shannon-Weiner Diversity with 95% confidence interval.

Explanatory Factor Regressions:

Lastly, we conducted national regressions of the rates of change of vegetation metrics against possible metrics that might explain shifts in the vegetation community. Sea Level Rise (last 19 years) and NERRS Landscape Condition were chosen because they were the two top variables that were selected from the LME (see Methods: Univariate - LME section). Slopes from regressions of vegetation metrics for each vegetation zone (of each site) and site were previously conducted and compiled (see **Data frames** section for details). Simple linear regressions using these slopes as the response variable were performed to understand if the change in Sea Level Rise or Landscape Condition had an effect on the ***rate of change*** for vegetation metrics (Unit = site or vegetation zone; Figure 8).

Experimental Unit:

1. Site
2. Vegetation Zone within Site

Analysis: Simple linear regressions

Regression Equation in R:

1. Vegetation Metric slope ~ Explanatory Factor

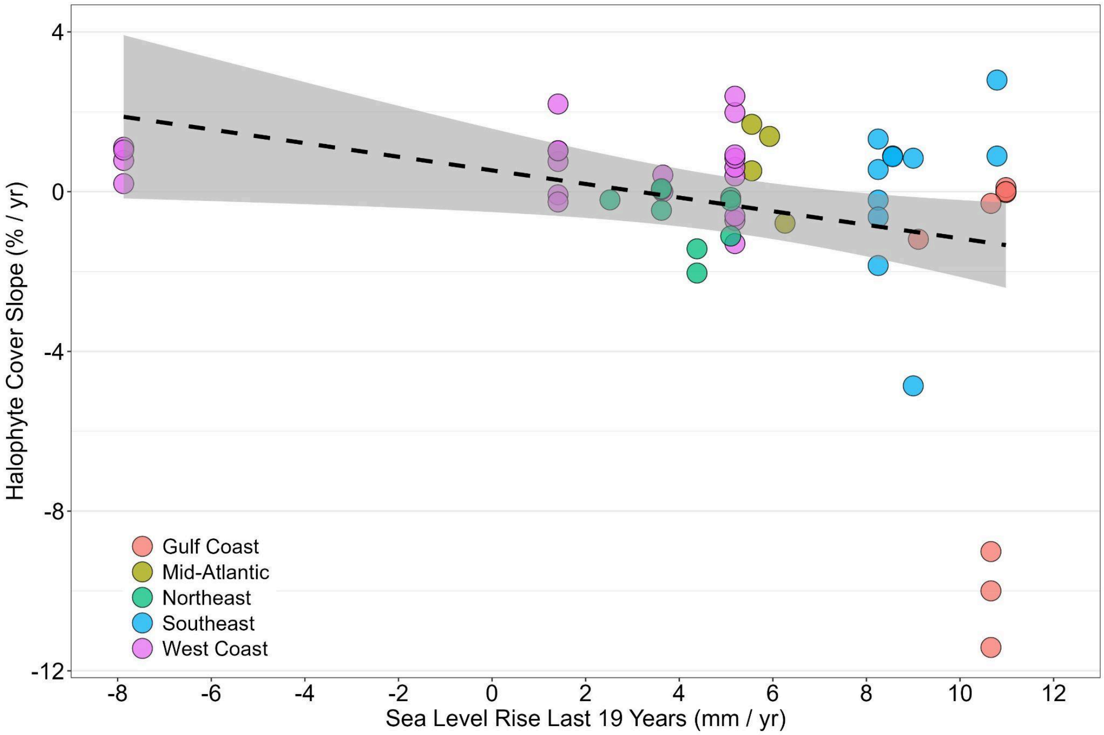


Figure 8: Simple linear regressions (exp. unit = site) of the slope of halophyte cover over sea level rise.

Methods: Univariate - LME Model Selection

Assessing Linear Mixed Effects models using AICc
National trends in four response variables (Ecotone Migration Index, percent live cover, Shannon-wiener Index, and salt to total ratio) were examined using Linear Mixed Effects Models (LME). LME's include both random effect (Reserve) and main effects (i.e., explanatory variables; Table 2), where main effects can include interactions between two or more explanatory variables. Main effects and interaction terms were assessed using a model selection process that compares model fit and complexity, using Akaike Information Criteria (AIC), across all candidate models to find the best statistical model for each response variable.

Associated Resources
- R coding for Univariate- LME Model Selection

Data Analysis Factors
Response Variables, rate of change (slope) in:
- Ecotone Migration Index (EMI)
- Live Cover
- Species Diversity (Shannon-Wiener Index),
- Salt tolerant to totalRatio

Random Effect
- Reserve

Explanatory Variables (excluded parameters; see Table 2 for details)
- Rate of SLR over previous 19yrs
- Proportion low marsh
- Salinity category (Oligohaline, Mesohaline, Polyhaline)
- Geomorphology (Riverine, Bay front, Back barrier)
- NERR Region
- Tidal range (Microtidal, Mesotidal, Macrotidal)
- NERRs Landscape resiliency condition (sum quantile)
- Relative SET change (rate of SET change minus rate of SLR over previous 19 yrs)

Table 2: Explanatory variables removal from the LME model assessment.

Variable	Reason for exclusion	Method of exclusion
NERRs Landscape resiliency condition (sum quantile)	Not available for the full dataset	Model selection run on subset of dataset and variable not present in full model
Rate of SET change minus rate of SLR over previous 19 yrs	SET data not available for the full dataset	Model selection run on subset of dataset and variable not present in full model
NERR Region	Multicollinearity between explanatory variables	Generalized Variance Inflation Factor (GVIF) Analysis
Tidal range (Microtidal, Mesotidal, Macrotidal)	Multicollinearity between explanatory variables	Generalized Variance Inflation Factor (GVIF) Analysis

Data Analysis Outline

Selecting Datasets:

Datasets were selected using the criteria outlined in the above Site Screening Process section. Additionally, model assessment was used to determine if fewer sites or fewer explanatory variables should be used in the final analyses. Of the 58 sites, 15 were missing data for two explanatory variables (Landscape Condition (4) and/or SET (15)). First we assessed the importance of the variables with missing data to determine if we should either remove the *sites* with missing data (i.e., use 43 sites with complete datasets and full list of explanatory variables) or remove the *variables* with missing data (i.e., use 58 sites and a subset of the full list of explanatory variables) from the final model assessment (models LME1-4 in Table 3). Since neither Landscape Condition nor SET variables were considered important in model selection (i.e., not present in best model; LME1-4 in Table 3) we re-ran the analysis using the full dataset (58 sites) and excluded these variables from model assessment (Table 2).

Developing Models:

A team of estuarine experts located across the nation (TWG and TAG) developed a causal diagram with, direct and indirect effects of explanatory variables on several response variables, with the intention of using Structural Equation Modelling (SEM; Grace 2010) to examine drivers of marsh change. Due to sample size requirements for complex SEM (5-20 observations per model parameter; Grace 2010) and missing data from multiple explanatory variables, the diagram was simplified and the team determined that model selection from a single complex model was more suited to this study. The team developed a full model with eight explanatory variables and interactions between rate of SLR and all other explanatory variables, and between proportion low marsh and all other variables (Figure 9). This potential model was assessed for multicollinearity between explanatory variables using Generalized Variance Inflation Factor (GVIF) Analysis (Fox and Monette 1992). A GVIF of less than five indicates low correlation between that explanatory variable and other variables in the model (James et al. 2013). Variables were sequentially removed if the GVIF values were greater than five, where the variable with greatest GVIF value was removed and GVIF analysis was rerun on the remaining variables until all variables had a GVIF value less than five. These variables were then included in the "full model" for model assessment.

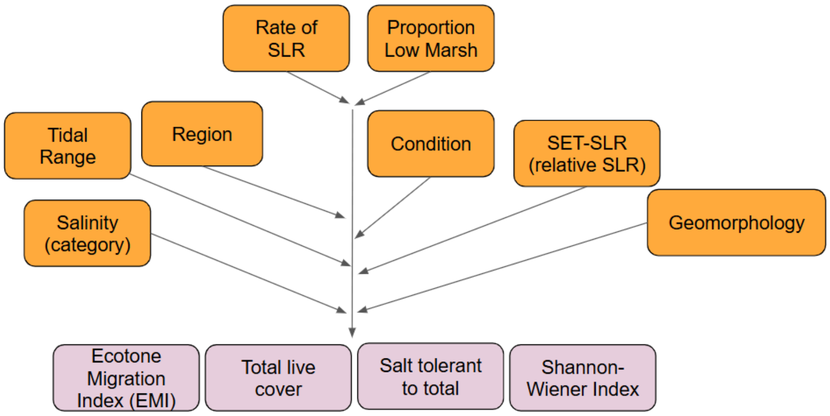


Figure 9: Conceptual model of 8 explanatory variables.

Assessing models

Full models were compared against all subset models. Using the 'dredge' function ('MuMln' package in R 4.2.1) a series of candidate models were created, which represented all possible combinations of main effects and interaction terms (Table 3). The full model was then compared to all candidate models as well as the null model (no explanatory variables) using Akaike Information Criteria with a small sample size correction factor (AICc). A delta AICc (difference between two candidate models) of more than 2 indicates a significant difference. Where the top models (models with lowest AICc) had a delta AICc >2 the model with the lowest AICc value was selected as the "best model". If the top models had a delta AICc less than two (considered not significantly different) then the simplest model (fewest variables) was selected as the best model.

Table 3: Full models used in model Linear Mixed Effect model (LME) assessment. Models LME 1-4 assessed all potential explanatory variables on a subset of data. Models LME 5-8 assessed the same response variables against a subset of explanatory variables on the full dataset. Four response variables were tested and include rate of change in: Ecotone Migration Index, Percent live cover, Shannon-Wiener Index and Salt to total proportion. Explanatory variables with superscript numbers indicate interactions between that variable and all other variables. Explanatory variables that were removed during Variance Inflation Factor (VIF) Analysis are included in the list but excluded from analysis and are indicated by a superscript x along with the GVIF value. Dataset includes either the full dataset or, if explanatory variables have missing data, a subset. Random effect is the same for all models. Number of candidate models is the number of models assessed and is based on the number of unique combinations of main and interaction terms produced from the full model.

Model	Response Variables	Explanatory Variables	Dataset	Random Effect	Number of models compared
LME1	Ecotone Migration Index	Salinity category Rate of SLR over previous 19yrs[1] Geomorphology NERRs Landscape resiliency condition Relative SET change Proportion low marsh[2] NERR Region$^{x(GVIF = 87.24)}$ Tidal range	Subset; 41 sites	Reserve	6768
LME2	Percent Live Cover				
LME3	Shannon-wiener Index				
LME4	Salt to total proportion				
LME5	Ecotone Migration Index	Salinity category Rate of SLR over previous 19yrs[1] Geomorphology Proportion low marsh[2] Region$^{x(GVIF = 77.5)}$ Tidal range$^{x\ (GVIF = 7.4)}$	Full; 56 sites	Reserve	72
LME6	Percent Live Cover				
LME7	Shannon-wiener Index				
LME8	Salt to total proportion				

[1] interactions between SLR and all other fixed effects

[2] interactions between proportion low marsh and all other fixed effects

Methods: Multivariate

Multivariate community ordination was used to visualize and analyze plant communities through cover data and explanatory variables across sites and vegetation zones, when appropriate (Table 4). Non-metric multidimensional scaling (NMDS) with loading factors (when appropriate) was used to visualize the data. Loading factors used included species or groupings (e.g., dominant species, bare, halophytes) or explanatory variables (e.g, distance to water, SLR). A PERMANOVA was also used to test for differences across explanatory variables (e.g., region, site, salinity, tide range, SLR). Cover and explanatory data used for all tests and visualizations in this section were estimates of change-through-time (i.e., slopes) at the plot scale, then averaged to zone-within-site and site (see Background>Dataframes for details).

<u>Questions:</u> Are marshes changing as indicated by plant community data? What characteristics do these changes have in common? (e.g., region, site, zone, salinity, tide range, SLR, etc)?

<u>Associated Resources</u>

- Github/swmpkim/nmst-national repository- scripts used for ordination are *00_national_multivariate_bySite.qmd* and *00_national_multivariate_byZone.qmd*, in the *R* folder

Table 4: Summary of multivariate tests

Exp. Unit	**Data**	**Loading factors**	**PERMANOVA**	**Notes**
Site	Plant community	Combination of dependent and explanatory variables	Region, Salinity, Geomorphology, Tidal range	-BIO-ENV performed -NMDS run with and without Gulf sites
Site	Explanatory variables	Explanatory variables	NA	NA
Zone	Plant community	Combination of dependent and explanatory variables	NA	-BIO-ENV performed
Plot	Plant community	Combination of dependent and explanatory variables	NA	-BIO-ENV performed -NMDS ran for each region separately

<u>Data Analysis Outline</u>

Multivariate analyses were conducted primarily at the site level, in the script *00_national_multivariate_bySite.qmd*, with the input file *slopesAndExpl_bySite.csv*. NMDS was also performed at both zone- and plot- levels, using the script *00_national_multivariate_byZone.qmd*.

Site Level

The **response matrix** was made up of the following variables, due to data completeness, ecological interest and consistency across of statistical tests and data summaries: *Total Unvegetated Slope; Total Live Vegetation slope; EMI slope; H.Halophyte slope; Species Richness slope; Shannon-Weiner Diversity Index slope.* Only one measurement from one site was missing (H.Halophyte_slope), at CBM-OPC, where no species were specified as H-Halophytes. This NA was replaced with 0.

Environmental variables used as overlays in NMDS and as the explanatory matrix in BIO-ENV match the key predictors chosen for the LME analysis included: *Geomorphology; Tidal Range; Salinity category; NERR Region; Landscape Resiliency condition; Sea Level Rise previous 19 yrs; SET change minus Sea Level Rise 19yr rate; proportion of plots at site in the "low" marsh group.*

Experimental unit: Site (n=56)

All quantitative variables were centered and scaled to 1 standard deviation before analysis. Distance matrices for the responses were based on Euclidean distance. For correlating the environmental variable matrix to the ordination (BIO-ENV procedure; 'bioenv' function in 'vegan' package), Gower's distance was used, as it can accommodate both factor variables and quantitative variables.

Separate PERMANOVAs were run on the response matrix for each categorical explanatory variable of interest, using the 'adonis2' function of the 'vegan' package. If there was a significant difference in response between categories ($p < 0.05$), PERMANOVAs were run between each pair of groups in that category (using the 'permanova_pairwise' function of the 'ecole' package).

Several ordinations were run on the response matrix. Explanatory variables were overlaid as loading arrows (continuous variables) or used as colors to differentiate categories (categorical variables). NMDS was used rather than PCA to avoid PCA's assumption of multivariate normality. Additionally, the technical working group was interested in using BIO-ENV, a procedure that was created to help interpret NMDS ordinations. Using NMDS allowed for the most appropriate and consistent ordinations. At the site level, Gulf sites made such a difference to results that ordinations were run both with and without them.

An additional ordination was performed on continuous environmental predictors: *condition, Latitude, proportion_low, SET_change, SET_minus_SLR_19yrs, siteAvg_distance_to_water, siteAvg_orthometric_height, and SLR_last19yrs*. This ordination was plotted with points colored by NERR Region, to illustrate differences between regions based on environmental factors (Figure 10).

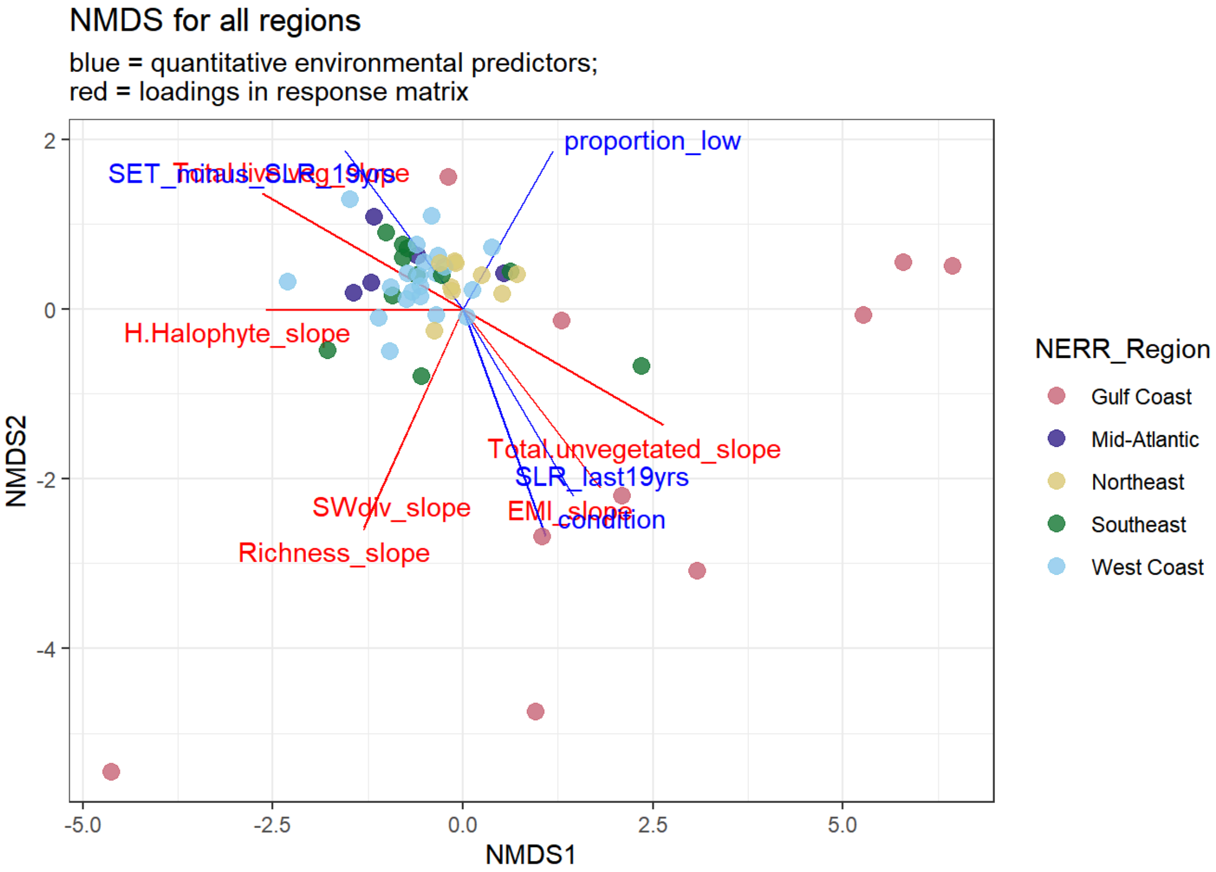


Figure 10: NMDS plot of 56 sites, including Gulf Coast sites, with 2-dimensional stress of 0.038. All variables from the response matrix are in red, the quantitative explanatory variables are in blue, and regions (also important according to BIO-ENV and PERMANOVA) are indicated by color.

Zone Level

The **response matrix** was made up of the following variables, due to completeness and ecological interest: *Total Unvegetated Slope; Total Live Vegetation slope; EMI slope; H.Halophyte slope; Species Richness slope; Shannon-Weiner Diversity Index slope*. Only two rows have missing data: H.Halophyte_slope at CBM-OPC Low and Mid, where no species were specified as H-Halophytes. These NAs were replaced with 0. Each row contained the average of plot-level observations at the zone (within site) level for a given date.

Environmental variables used as overlays in NMDS and as the explanatory matrix in BIO-ENV match the key predictors chosen for the LME analysis included: *Geomorphology; Tidal Range; Salinity category; NERR Region; Vegetation Zone; Landscape Resiliency condition; Sea Level Rise previous 19 yrs; SET change minus Sea Level Rise 19yr rate.*

Experimental unit: Zone within site (n = 114)

All quantitative variables were centered and scaled to 1 standard deviation before analysis. Distance matrices for the responses were based on Euclidean distance. For correlating the environmental variable matrix to the ordination (BIO-ENV procedure; ‘bioenv’ function in ‘vegan’ package), Gower’s distance was used, as it can accommodate both factor variables and quantitative variables.

NMDS and BIO-ENV were performed using the variables given above (Figure 11).

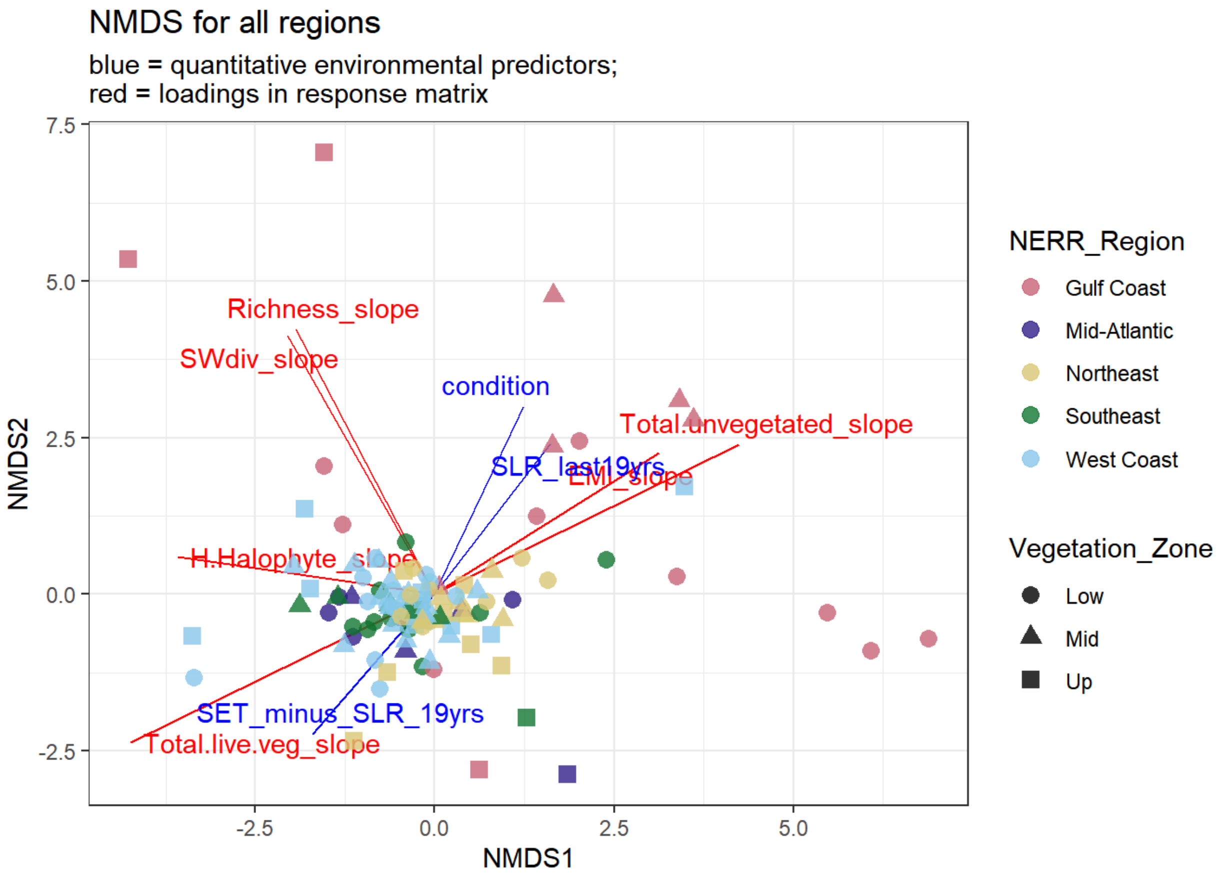


Figure 11: NMDS plot of 114 zones-within-sites with a 2-dimensional stress of 0.079. This looks a lot like a rotated version of the site-level NMDS. The outliers in the upper left are ‘Up’ zones along the Gulf Coast, and on the far right are ‘Low’ zones along the Gulf Coast (MAR specifically).

Plot Level

The **response matrix** was made up of the following variables, due to completeness and ecological interest: *Total Unvegetated Slope; Total Live Vegetation slope; EMI slope; Species Richness slope; Shannon-Weiner Diversity Index slope*. Each row was an individual plot's observations for a given date.

Environmental variables used as overlays in NMDS and as the explanatory matrix in BIO-ENV match the key predictors chosen for the LME analysis included: *Geomorphology; Tidal Range; Salinity category; NERR Region; Vegetation Zone; Landscape Resiliency condition; Sea Level Rise previous 19 yrs; SET change minus Sea Level Rise 19yr rate.*

Experimental unit: Individual plots (n = 1831)

All quantitative variables were centered and scaled to 1 standard deviation before analysis. Distance matrices for the responses were based on Euclidean distance. For correlating the environmental variable matrix to the ordination (BIO-ENV procedure; 'bioenv' function in 'vegan' package), Gower's distance was used, as it can accommodate both factor variables and quantitative variables.

NMDS and BIO-ENV were performed using the variables given above (Figure 12). NMDS results were broken out by region for plot-level graphics (Figure 13).

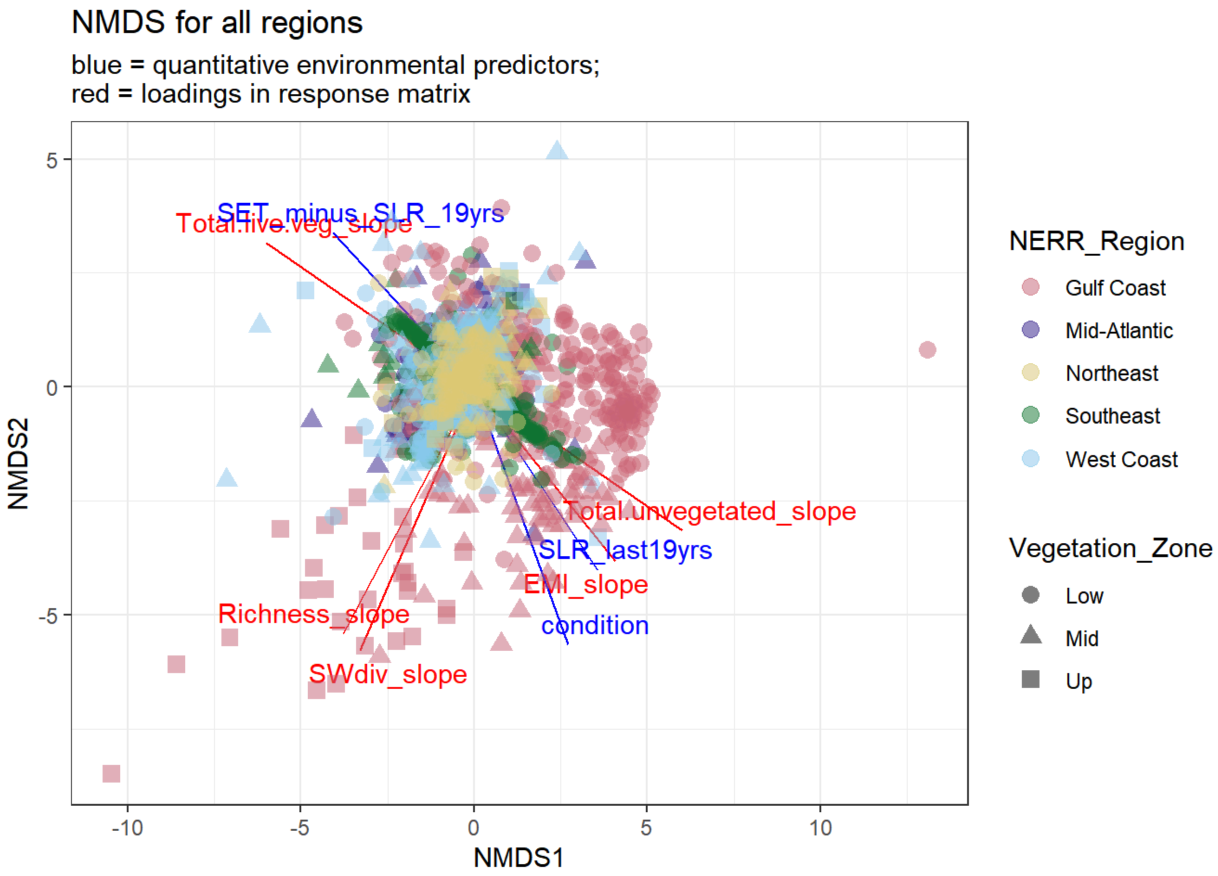


Figure 12: NMDS plot of 1831 plots from all sites, with a 2-dimensional stress of 0.076. Gulf Coast sites have the greatest spread, though further interpretation is difficult with this figure. Plots were also broken out by region.

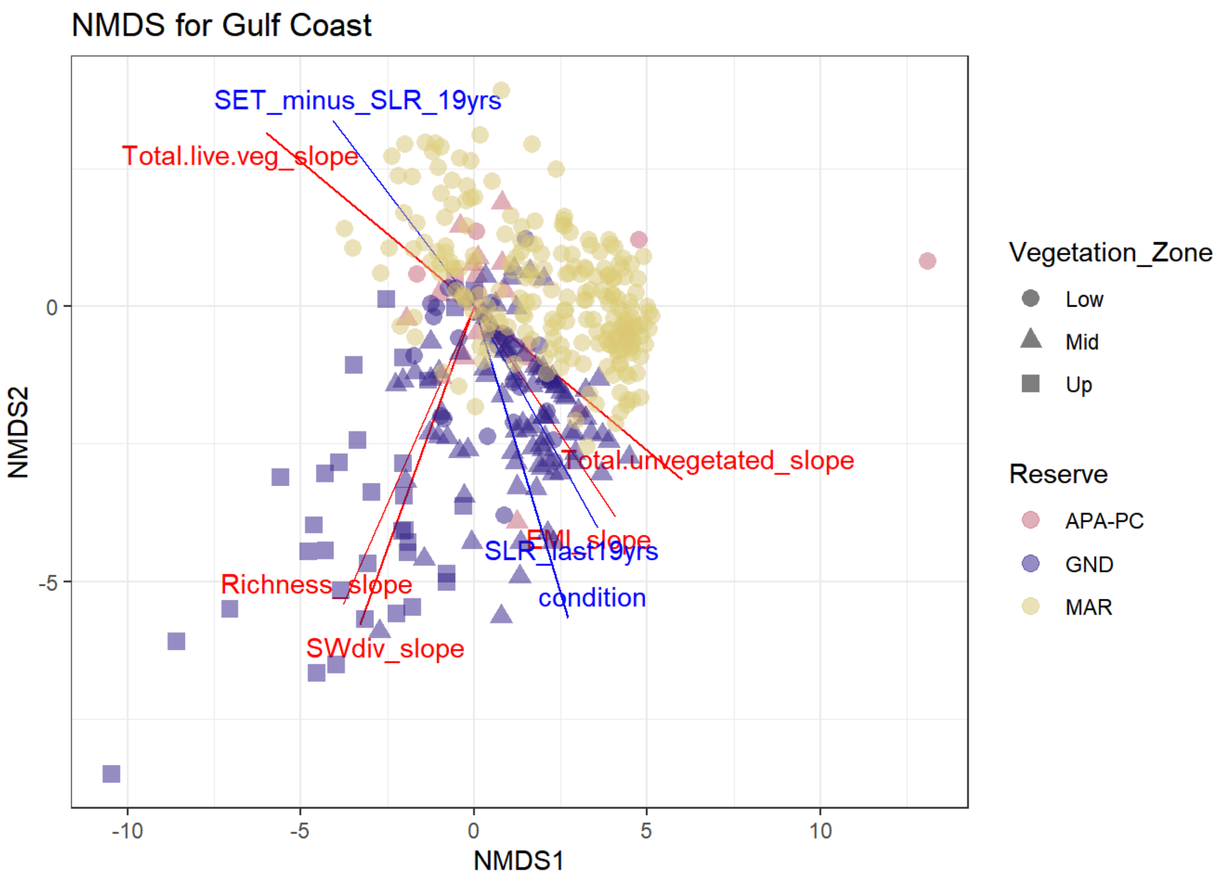


Figure 13: NMDS of Gulf Coast plots. All variables from the response matrix are in red, the quantitative explanatory variables are in blue, sites are indicated by color and vegetative zone by shape.

Other Ordination notes

- SIMPER (contributions to similarity analysis) were not run because SIMPER only works for a community matrix; it's meant to describe what contributes to Bray-Curtis dissimilarities. We did not use Bray-Curtis because it requires all positive data; our responses were "change through time" and thus, some values were negative. We instead used Euclidean distances on centered and scaled (to 1 SD) data for all other multivariate analyses.
- Magnitude of Community Change (MoCC) was also not run due to data constraints and constraints on time and budget. Similar to PERMANOVA, MoCC quantifies change of a community through 2D (or more) space over time using Euclidean distances from community data in an ordination matrix. Dissimilar PERMANOVA, MoCC examines change, paired for each exp unit (plot, zone or site).
    - Since we used NMDS, which does not preserve exact distances and is not based on eigenvalues (does not give the same results every time like PCA or PCoA), we did not run this test. Trajectory analysis may be a future way to address this issue (De Caceres 2025).

Results: Univariate - Summary Analysis

Vegetation communities are changing at different scales

Vegetation communities at the site, regional, and national scales are changing based on site-level and the national regressions (Table 5, Figure 14). National regressions across the study, irrespective of vegetation zone or site characteristic, identified live cover, halophyte cover, EMI, and salt ratio as four significant trends nationally. Live cover declined at a rate of 0.58% annually (F = 10.9, p = 0.001), halophyte cover declined at similar rate of 0.55% annually (F = 11.2, p = 0.001), EMI increased at 0.006 annually (F = 22.3, p < 0.001), and salt ratio declined at a rate of -0.006 (F = 18.6, p < 0.001); all indicators of sea-level-rise (SLR). Trends over time were not significant for the remaining vegetation metrics (freshwater cover, species richness, Shannon-Weiner diversity). At the regional scale, vegetation metrics changed more often in the Northeast, Gulf Coast, and Mid-Atlantic. In the Gulf Coast and Northeast, live and halophyte cover decreased and EMI increased, all indicators of SLR. The Gulf Coast experienced sharp declines in vegetation cover with annual declines of -3.1 ± 1.5 % and 5.6 ± 1.4 % for halophyte and live cover, respectively (Table 5). The rate of EMI change was a greater factor in the Northeast and Gulf Coast than the other regions. The Mid-Atlantic, however, experienced increases in live (1.0 ± 0.8 %), halophyte (0.6 ± 0.5 %), and freshwater cover (0.5 ± 0.5 %). Sites in the Mid-Atlantic were predominantly lower salinity tidal marshes (fresh, oligo- and mesohaline). The significant national trends in the vegetation community spurred the investigation of changes in the vegetation community at smaller scales (plot and zone).

Table 5: Slopes of selected vegetation metrics aggregated across site-level regressions for the national and regional scales. Slopes are reported as mean +/- standard error.

	National	Northeast	Mid-Atlantic	Southeast	Gulf Coast	West Coast
Live Cover	-0.90 +/- 0.42	-0.47 +/- 0.27	1.00 +/- 0.81	0.24 +/- 0.59	-5.63 +/- 1.36	0.11 +/- 0.26
Halophyte Cover	-0.37 +/- 0.35	-0.66 +/- 0.25	0.56 +/- 0.45	0.11 +/- 0.64	-3.08 +/- 1.54	0.58 +/- 0.20
Freshwater Cover	-0.01 +/- 0.078	-0.02 +/- 0.06	0.51 +/- 0.51	0.08 +/- 0.09	-0.41 +/- 0.32	0.02 +/- 0.01
Ecotone Migration Index	0.009 +/- 0.003	0.011 +/- 0.002	0 +/- 0.005	0.003 +/- 0.005	0.036 +/- 0.010	0 +/- 0.002
Salt Ratio	-0.005 +/- 0.003	0.001 +/- 0.001	0 +/- 0.001	-0.012 +/- 0.006	-0.021 +/- 0.014	0.002 +/- 0.001
Species Richness	0.008 +/- 0.006	0 +/- 0.025	0.006 +/- 0.022	0.014 +/- 0.012	0.075 +/- 0.108	0.010 +/- 0.013
Shannon-Weiner	0.020 +/- 0.020	-0.007 +/- 0.006	-0.003 +/- 0.007	0.008 +/- 0.005	0.025 +/- 0.031	0.009 +/- 0.004

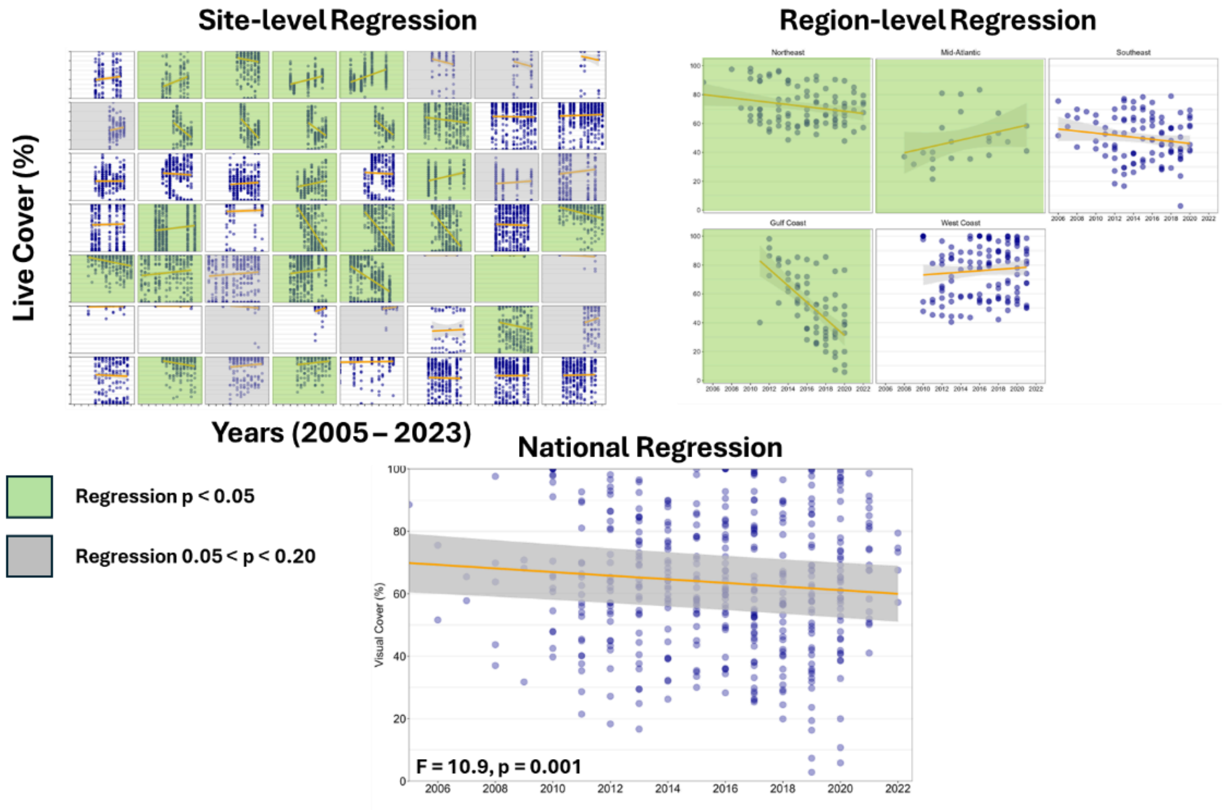


Figure 14: Univariate analysis analyzed changes in vegetation communities of live cover at the site (top left), region (top right), and national (bottom) scales. Site and region trends highlighted in green are significant ($p < 0.05$) and in light grey are tending significant ($0.05 < p < 0.20$).

Impact of Vegetation Zone on Changes in Vegetation Community

Vegetation zone in the national dataset were lumped from eleven separate options reported by Reserves into three broad categories: Low (Mudflat, Seaward Edge, Low Marsh, Pannes/Pools), Mid (Transition, HIgh Marsh) and Up (Upland Edge, Freshwater Tidal, Upland). From a national perspective, changes in vegetation cover were impacted by the vegetation zone and implicitly, elevation, but only for the EMI metric (Interaction: $F = 16.3$, $p < 0.001$; Figure 15 – Left). Vegetation communities shifted inland according to EMI at similar rates for Low and Mid elevation plots (0.009 and 0.011 yr^{-1}, respectively) whereas plots closer to the upland shifted inversely at a similar rate (- 0.014 yr^{-1}). Interestingly, with vegetation zone, the EMI compilation analysis showed greater EMI scores (combination of slope and trend significance) in the Mid plots (0.62 ± 0.16) compared to the Low (0.24 ± 0.17) and Up plots (-0.13 ± 0.21; Figure 15 – Right). It should be noted that Up plots constituted only 6% of the total national plot dataset for NAMASTE, and they were not monitored for several sites. The uneven sample size and monitoring across the country may contribute to lack of differences between low and up plots. The negative trend in the EMI in the upper edges of tidal marshes demonstrates that tidal marshes are not changing as predicted.

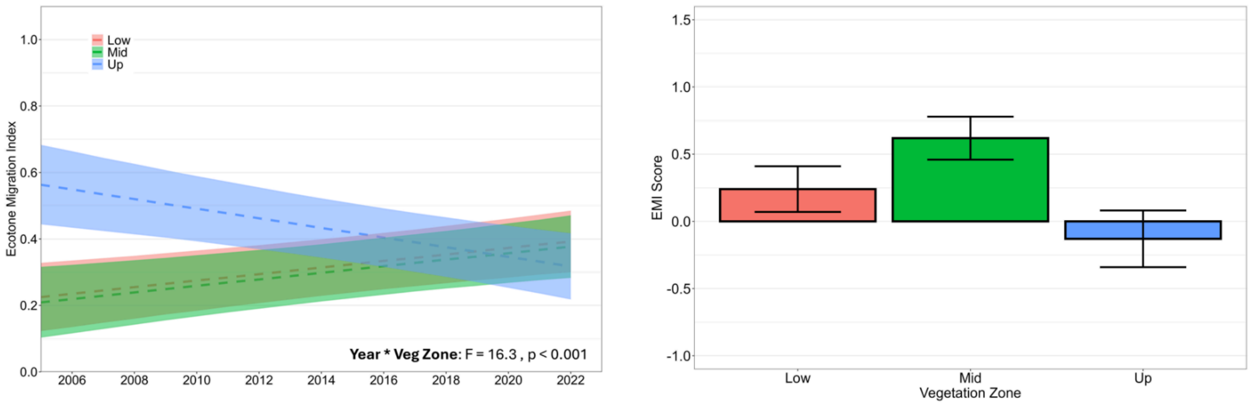


Figure 15: National regression of EMI at the site level over time (left). The trend of EMI over time varied by vegetation zone (F = 16.3, p < 0.001). Compilation analysis of EMI based on the p-value and slope of site-level regressions (right). Regressions and values are reported as mean +/- standard error.

<u>Vegetation Community Changes Varies by Region</u>

The Northeast and Gulf Coast experienced substantial declines in live and halophyte cover according to the national mixed linear regressions (Interactions in Live**:** F = 36.3, p < 0.001 and Halophyte: F = 23.9, p < 0.001; Figure 16). Vegetation communities shifted the greatest upslope at the same regions based on the EMI from both the national regression (F = 4.1, p = 0.017) and the EMI compilation analysis with scores of 1.7 +/- 0.2 and 1.3 +/- 0.3, in the Northeast and Gulf Coast, respectively. The Mid-Atlantic also experienced significant changes yet in the opposite direction with net gains in several metrics. Live, halophyte, and freshwater cover increased over time at rates similar to or greater in magnitude than the Northeast. Interestingly, the Mid-Atlantic region was the only region with annual changes of freshwater cover greater than 0.5 % (2.6 % for the region). The Mid-Atlantic region also had the second greatest positive slopes for live and halophyte cover across regions when site-level regressions were averaged, possibly due to most sites in this region being predominantly lower salinity (see discussion in the next section).

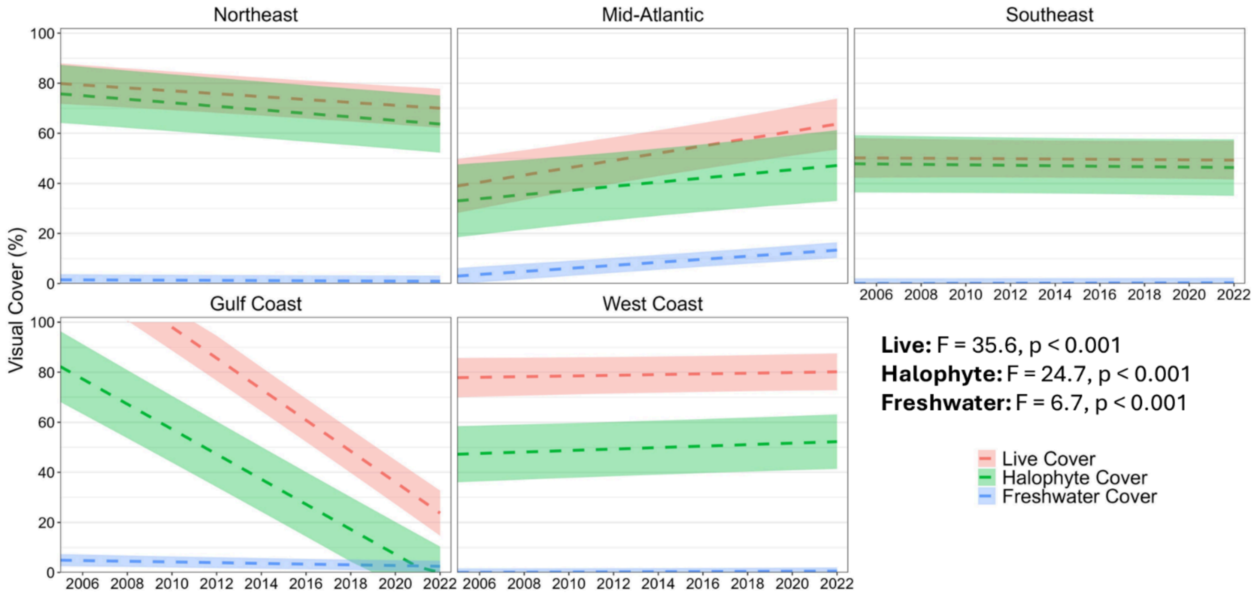


Figure 16: National regressions of live cover, halophyte cover, and freshwater cover shown for each region. The interaction of time and region were significant for each vegetation metric ($p < 0.05$). Regressions reported as mean +/- standard error.

Vegetation Changes Varied by Salinity Regime

National mixed regressions of the summarized site level data revealed a pattern of declining vegetation cover and inland shift of vegetation communities as salinity increased in the estuary. The trend of halophyte cover over time was different between the three salinity regimes (Interaction: F = 5.7, p = 0.004), where halophyte cover increased at similar rates in oligohaline systems and mesohaline systems (+0.49 and +0.37% yr^{-1}, respectively) and declined in polyhaline systems (-0.90 % yr^{-1}) (Figure 17 – Top Left). Live cover experienced starker changes over time broken down by salinity regime (F = 6.8, p = 0.001), where overall vegetation cover declined in both mesohaline and polyhaline systems (-0.20 and -0.97% yr^{-1}) and increased in oligohaline systems (+0.91% yr^{-1}) (Figure 17 – Top Right). From the perspective of vegetation communities shifting, the EMI also varied by salinity regime (F = 4.2, p = 0.016), where EMI overall increased for mesohaline and polyhaline systems and declined with oligohaline systems (Figure 17 – Bottom). The compilation analysis of EMI supported the finding of the national analysis of salinity regime.

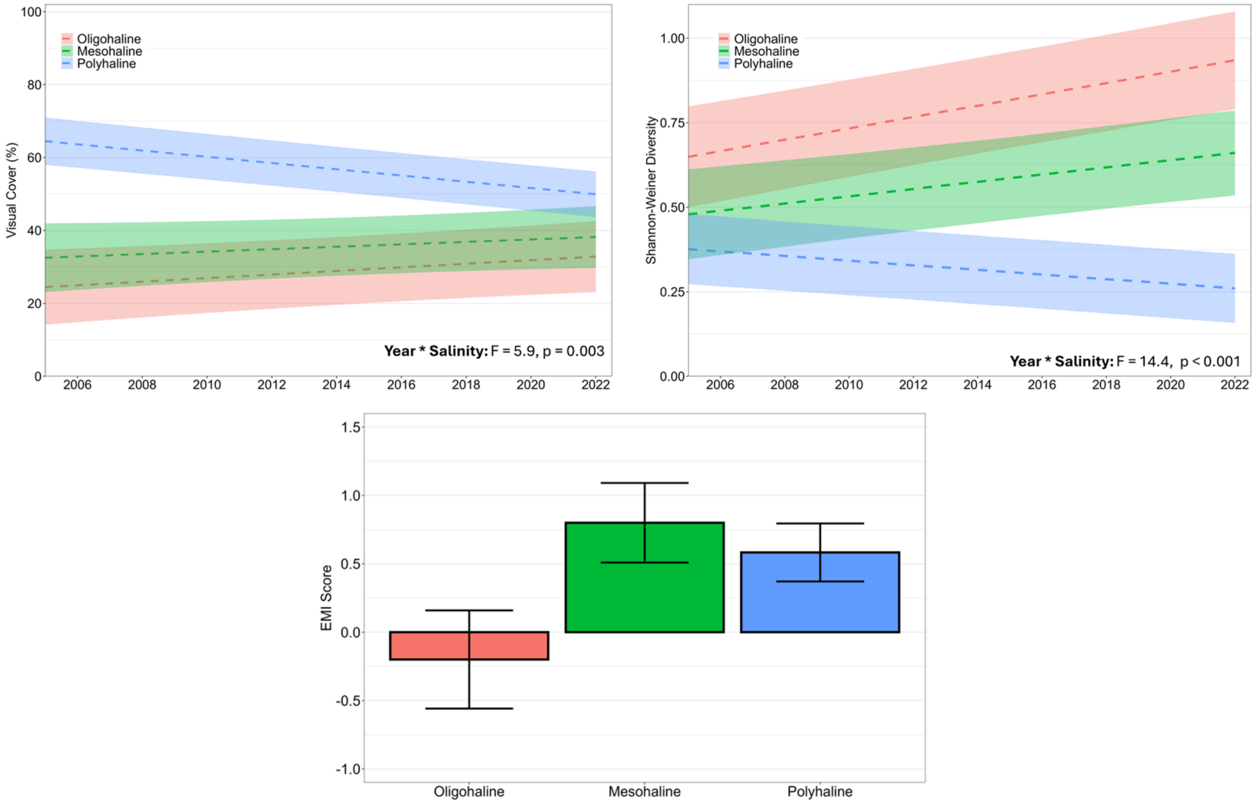


Figure 17: National regression of halophyte cover broken down by salinity regime (top left), National regression of Shannon-Weiner Diversity broken down by salinity regime (top right), and Compilation analysis of EMI of salinity regimes (bottom). Values and regressions reported as mean +/- standard error.

Impact of Sea Level Rise on Vegetation Community Shifts

The rate of sea level rise was evaluated as a possible factor of the rate of change for various vegetation metrics at the vegetation zone and site level. The rate of halophyte cover change and EMI were correlated with sea level rise (Figure 18 – Left). The change in halophyte cover declined over greater sea level rise (F = -2.4, p = 0.022, R^2 = 0.08) shifting from halophyte increases to absolute declines at roughly 4 mm yr^{-1} of SLR. The change in EMI increased over greater sea level rise (F = 3.0, p = 0.005, R^2 = 0.12) suggesting greater plant community migration. Vegetation-level regressions of SLR found that the halophyte change trend was similar across vegetation zones (SLR Term: F = 6.6, p = 0.012, Interaction: F = 1.6, p = 0.22). However, the impact of SLR on the rate of EMI was influenced by vegetation zone (F = 3.3, p = 0.040), where low and mid elevation plots saw increasing EMI and upper elevation plots had decreasing EMI over increasing SLR (Figure 18 – Right). The results of the upper marsh plots may be the result of an unpredicted pattern and/or due to low replication; comprising only 6% of the total plots.

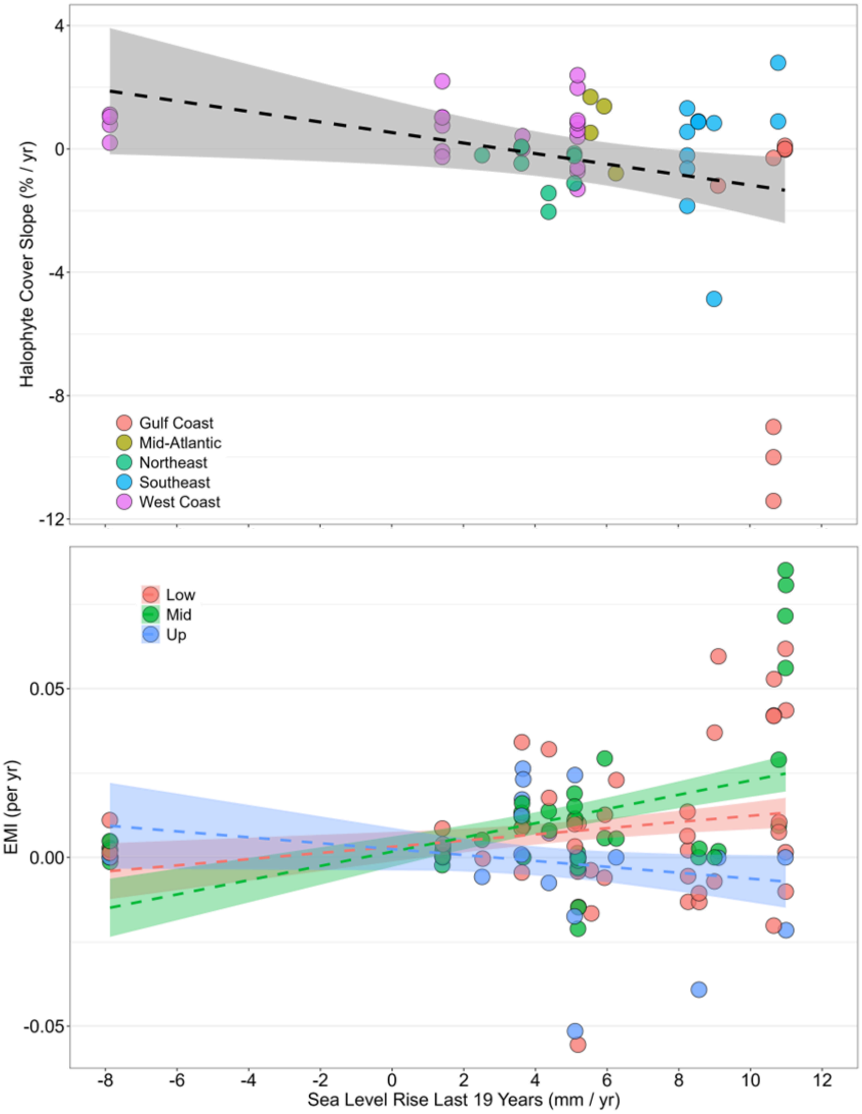


Figure 18: Impact of sea level rise on the rate of change of halophyte cover nationally (top). Impact of sea level rise on the rate of ecotone migration index broken down by vegetation zone (bottom). Regressions reported as mean +/- 95% confidence interval.

Results: Univariate- LME Models

Model assessment results for all models LME 1-8 are summarized in Table 6. Since there were no benefits to using a subset of the data to assess additional variables (i.e. additional variables were not included in either best model) only models with greater replication (LME 5-8) are included in output summaries (Table 7) and figures (Figures 19-22).

Table 6: Top models example for EMI in model selection process as defined as the model with the lowest AICc value and all models with an AICc within 2 points of this lowest value. Models with a delta AIC (ΔAIC) < 2 are considered equivalent, therefore the best model is defined as the simplest model in the top model list (indicated by a * and **bold font**). Explanatory variables in models which include interaction effects are indicated by superscripts. Model weights range from 0-1 where the sum of all models equals 1 and higher weights indicate stronger support for the model. Weights are calculated by dividing the relative likelihood (exp(-0.5*ΔAIC) of each model by the sum of all likelihoods.

Model	**Response**	**"Top Models" with delta AICc <2**	**Justification for model selection**	**Weight of Best model and sum of weights for Top models**	**Sample size**	**No. of models with ΔAICc <2 / No. of candidate models**
LME1	EMI	***Model 1: AICc = -202.6** ***Explanatory Variables:*** **Salinity category** **Rate of SLR over previous 19yrs** Model 2: AICc = -202.1 (ΔAICc 0.43) *Explanatory Variables:* Salinity Rate of SLR^1 Condition^1 Model 3: AICc = -202.0 (ΔAICc 0.57) *Explanatory Variables:* Salinity category^2 Rate of SLR over previous 19yrs^2 Model 4: AICc = -201.2 (ΔAICc 1.34) *Explanatory Variables:* Salinity category Rate of SLR Condition	Best model is both the lowest AICc model and the simplest model	0.063 (Best) 0.194 (Sum of Top)	41	4/6768
LME2	Percent Live Cover	Model 1: AICc = 199.3 *Explanatory Variables:* Geomorphology^{1,2} Proportion low marsh Salinity	Simplest model out of top models (one	0.143 (Best) 0.289 (Sum of Top)	41	3/6768

		Rate of SLR ^{2} Model 2: AICc = 200.4 (ΔAICc 1.15) *Explanatory Variables:* Geomorphology Proportion low marsh^{1,2} Salinity ^{1} Rate of SLR ^{2} ***Model 3: AICc = 100.9** **(ΔAICc 1.58)** ***Explanatory Variables:*** **Geomorphology** **Proportion low marsh^{1}** **Salinity ^{1}** **Rate of SLR**	interaction term)			
LME3	Shannon-wiener Index	Model 1: AICc = -171 *Explanatory Variables:* Proportion low marsh^{1} Salinity^{2} Relative SET^{3} Rate of SLR ^{1,2,3} Model 2: AICc = -170.4 (ΔAICc 0.54) *Explanatory Variables:* Proportion low marsh^{1,2} Salinity^{1,3} Relative SET^{4} Rate of SLR ^{2,3,4} Model 3: AICc = -170.2 (ΔAICc 0.78) *Explanatory Variables:* Proportion low marsh^{2,3} Salinity^{4} Rate of SLR ^{2,4} Condition^{3} Model 4: AICc = -169.3 (ΔAICc 1.70) *Explanatory Variables:* Proportion low marsh^{1} Salinity^{2} Relative SET^{3} Rate of SLR^{2,3}	Poor model selection	0.108 (Best) 0.355 (Sum of Top)	41	5/6768

		Condition[1] Model 5: AICc = -169.2 (ΔAICc 1.78) *Explanatory Variables:* Proportion low marsh[1,2] Salinity[3] Relative SET[1,4] Rate of SLR[2,3,4]				
LME4	Salt to total proportion	***Model 1: AICc = -338.8** ***Explanatory Variables:*** **Salinity category[1]** **Rate of SLR over previous 19yrs[1]** *Model 2:* AICc = -338.2 (ΔAICc 0.61) *Explanatory Variables:* Condition Salinity[1] Rate of SLR over previous 19yrs[1]	Best model is both the lowest AICc model and the simplest model	0.233 (Best) 0.405 (Sum of Top)	41	2/6768
LME5	EMI	Model 1: AICc = -291.1 *Predictor Variables:* Salinity category[1] Rate of SLR over previous 19yrs[1] Model 2: AICc = -290.3 (ΔAICc 0.83) *Predictor Variables:* Salinity category[1] Rate of SLR over previous 19yrs[1] Geomorphology ***Model 3: AICc = -290.2** **(ΔAICc 0.90)** ***Predictor Variables:*** **Salinity category** **Rate of SLR over previous 19yrs**	Simplest model out of the top models	0.127 (Best) 0.458 (Sum of Top)	56	3/72

LME6	Percent Live Cover	***Model 1*: AICc = 258.9** ***Predictor Variables:*** **Geomorphology^{1}** **Proportion low marsh^{2}** **Salinity category^{2}** **Rate of SLR over previous 19yrs^{1}** Model 2: AICc = 260.1 (ΔAICc 1.19) *Predictor Variables:* Geomorphology^{1} Proportion low marsh^{2,3} Salinity category^{2} Rate of SLR over previous 19yrs^{1,3}	Simplest model also has the lowest AICc	0.416 (Best) 0.646 (Sum of Top)	56	2/72
LME7	Shannon-wiener Index	***Model 1*: AICc = -216** ***Predictor Variables:*** **Proportion low marsh^{1,2}** **Salinity category^{1,3}** **Rate of SLR over previous 19yrs^{2,3}**	Only one model in top models	0.481 (Best) 0.481 (Sum of Top)	56	1/72
LME8	Salt to total proportion	***Model 1: AICc = -371.4** ***Predictor Variables:*** **Proportion low marsh^{1}** **Salinity category^{1}**	Only one model in top models	0.628 (Best) 0.628 (Sum of Top)	56	1/72

Table 7: Slope (including sign) and intercept for each predictor in our "Best Models". Interactions are indicated by superscripts in the Predictor column and include a different slope for each predictor category; where no interactions were present in the best model, slope is the same for each categorical level. Estimates of the proportion of variance explained by the fixed effects only (Marginal R^2; R^{2}m) and the full model including both fixed and random effects (conditional R^2; R^{2}c) are included.

Model	**Response Variables**	**Predictor**	**Intercept**	**Slope**	**R^{2}m and R^{2}c**
LME5	EMI	Rate of SLR over previous 19yrs		+0.002	0.24 and 0.54
		Salinity category			
		- Oligohaline	0.010		
		- Mesohaline	-0.015		
		- Polyhaline	0.002		
LME6	Percent Live Cover	Rate of SLR over previous 19yrs^1			0.60 and 0.68
		Geomorphology^1			
		- Back Barrier	check these intercept	-0.06	
		- Bay Front		-14.94	
		- Riverine		NA	
		Proportion low marsh^2			
		Salinity category^2		-0.50	
		- Oligohaline	1.96	11.64	
		- Mesohaline	-5.42	-3.24	
		- Polyhaline	1.41		
LME7	Shannon-wiener Index	Proportion low marsh^{1,2}			0.55 and 0.60
		Salinity category^{1,3}			
		- Oligohaline	0.023	-0.012	
		- Mesohaline	0.009	0.002	
		- Polyhaline	-0.036	-0.011	
		Rate of SLR over previous 19yrs^{2,3}			
		Salinity category^{1,3}			
		- Oligohaline	0.023	0.014	
		- Mesohaline	0.009	0.006	
		- Polyhaline	-0.036	0.006	
LME8	Salt to total proportion	Proportion low marsh^1			0.46 and 0.46
		Salinity category^1			
		- Oligohaline	0.035	-0.039	
		- Mesohaline	-0.012	0.026	
		- Polyhaline	0.004	-0.004	

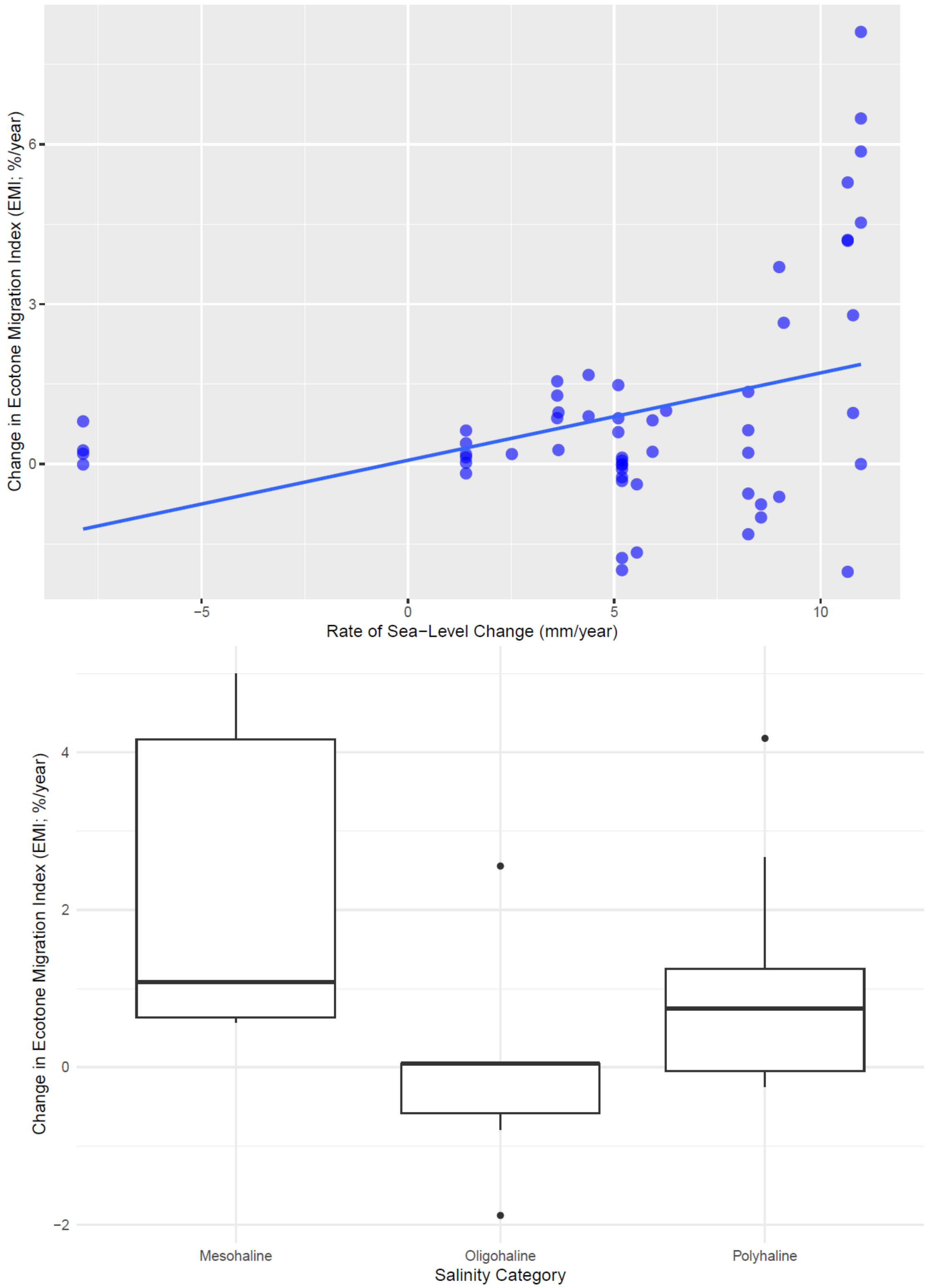


Figure 19: LME 5 Best Model results showing positive relationship between change in Ecotone Migration Index (top) and rate of sea-level rise and rate of EMI for each salinity variable (bottom).

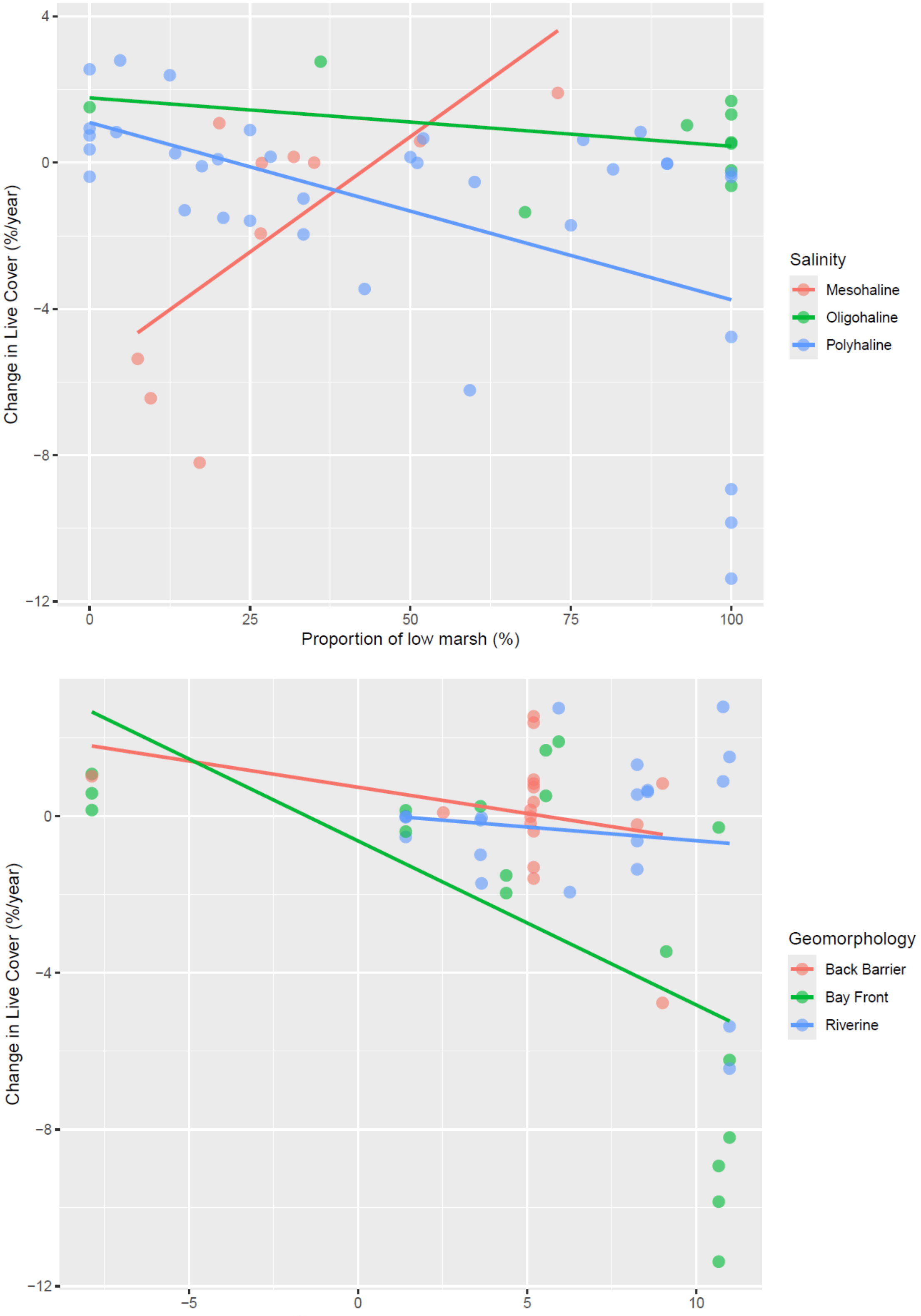


Figure 20: LME 6 Best Model showing interactions between proportion of low marsh and salinity (top) and between rate of SLR and geomorphology for explaining change in live cover (bottom).

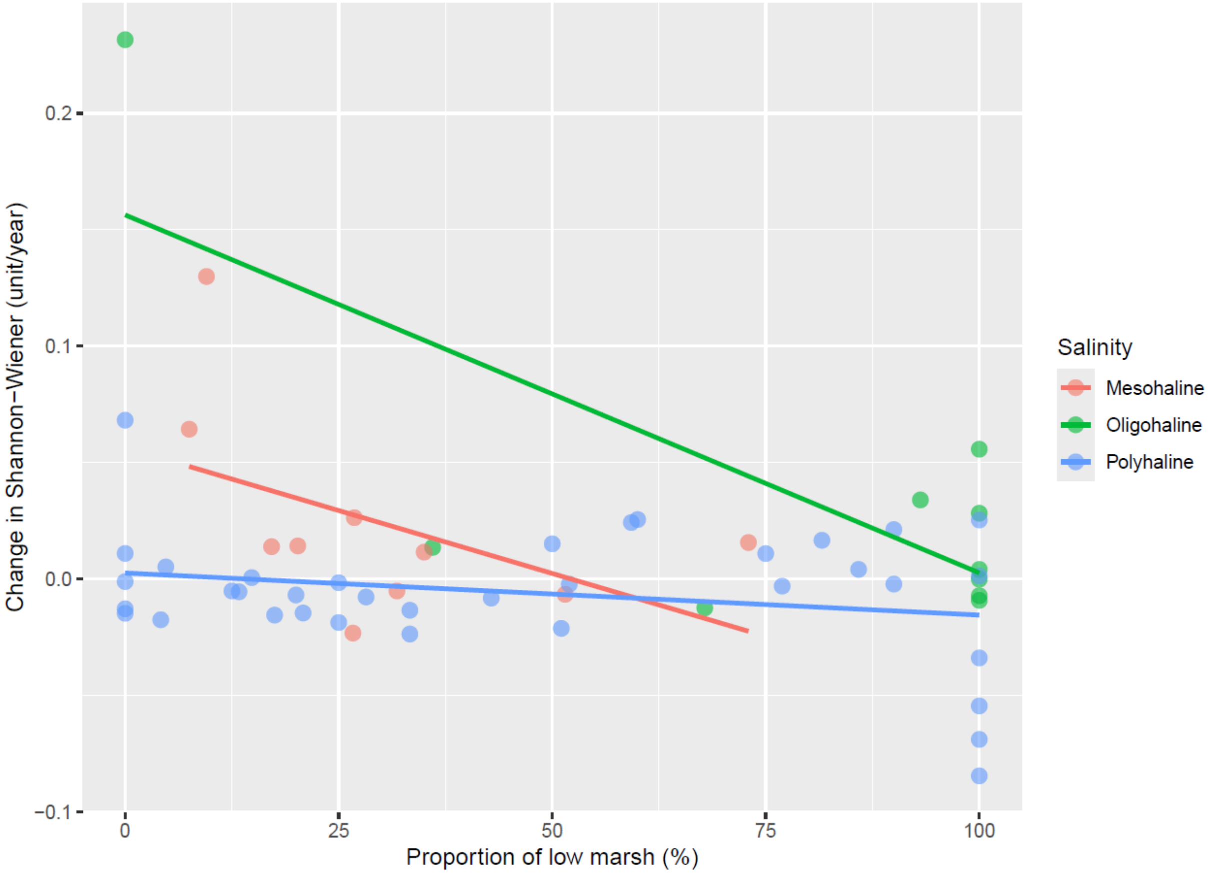


Figure 21: LME 7 Best Model results, figure shows interaction between proportion low marsh and salinity for explaining change in Shannon-wiener Index. The Shannon-wiener index ranges from 0 to 1, where higher values indicate greater diversity. Points with positive values on the y-axis represent sites that increased in diversity (i.e., increased Shannon-wiener value) and points with negative values decreased in diversity. Trend lines show that marshes with greater proportions of low marsh experienced relatively less change and greater decreases in diversity over time compared to marshes with proportionally less low marsh, which experienced greater increases in diversity. This trend is more pronounced in lower salinity marshes (Oligohaline and Mesohaline) compared to higher salinity marshes (Polyhaline).

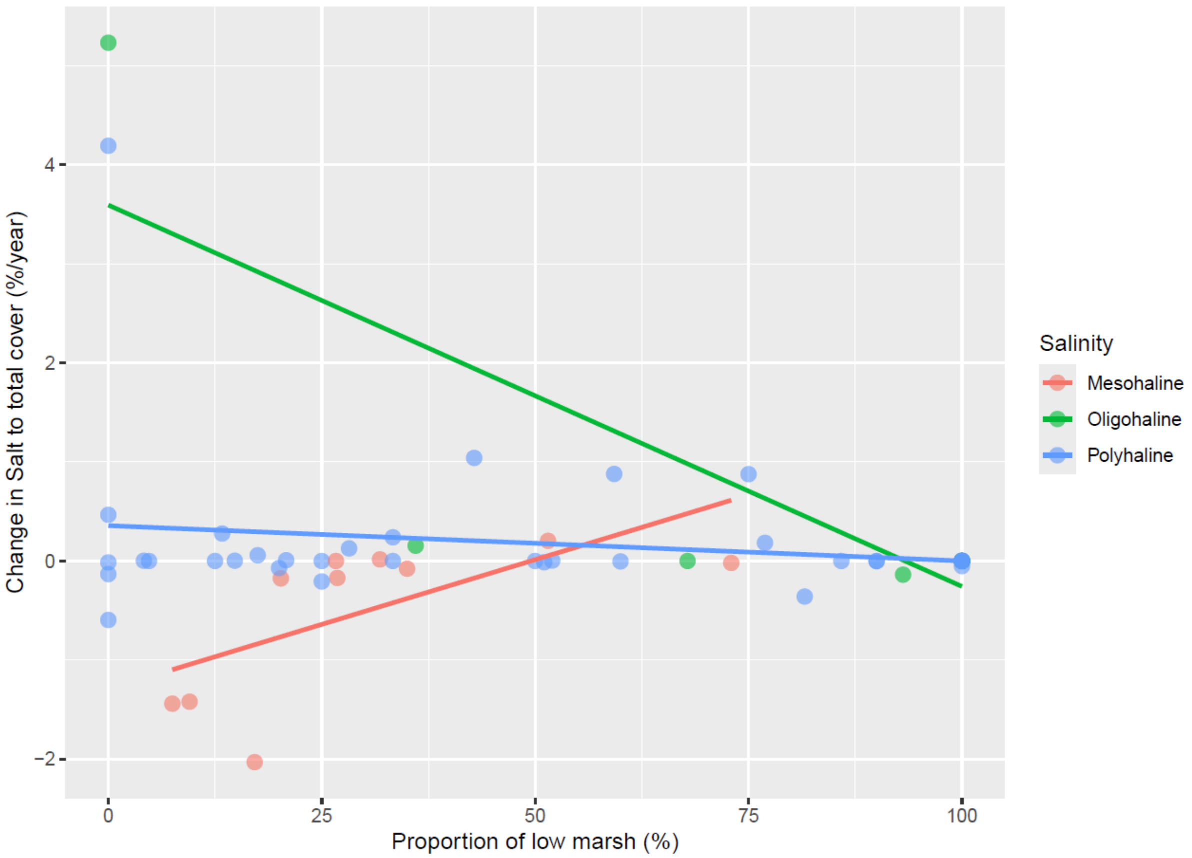


Figure 22: LME 8 Best Model showing interactions a) between proportion low marsh and salinity for explaining change in salt to total cover. For Mesohaline marshes (mid salinity levels) salt to total cover mostly decreased over time where marshes with proportionally less low marsh experienced greater decreases. Polyhaline marshes were relatively consistent with salt to total cover proportions. Note: one marsh with higher proportions of salt to live cover is driving the negative trend in Oligohaline marshes.

Results: Multivariate

Overall Takeaways

At the site-level, the PERMANOVA indicated response matrix differences for NERR Region, geomorphology, and salinity category. At the site-level, best predictors from BIO-ENV were SLR, NERR Region, and landscape resiliency condition when including all sites, with Spearman correlation between the response matrix and environmental matrix of 0.334. When removing Gulf Sites, the best predictors changed to salinity category, NERR Region, and proportion of site that is low marsh: the Spearman correlation between those matrices was 0.130.

At the zone and plot level, the best predictors from BIO-ENV included NERR region, vegetation zone, and landscape resiliency condition at both levels. The zone level additionally included the salinity category as a best predictor. The Spearman correlation between the response and environmental matrices at the zone-level was 0.309, and at the plot-level was 0.188.

At all levels, NERR Region is a very important predictor of vegetation community changes. Notably, the Northeast tends to be different from 2-3 other regions and the Gulf Coast region is changing in different ways than the other four regions: this is demonstrated by PERMANOVA results and with Gulf sites as outliers in ordinations. The removal of Gulf Coast sites from ordinations changed the relationship between the response matrix and two predictors (landscape resiliency conditions and proportion of low marsh), and changed which predictors were most important. NERR Regions are characteristically different and are well separated by rate of sea level rise and latitude, based on the NMDS of environmental predictors. Within regions, variables including the proportion of a site that is low marsh, landscape resilience condition, and distance to water seem to separate out the sites. In addition to NERR Region, landscape resilience condition and vegetation zones, when included, are the other top predictors for the response matrix.

Site Level

File: *2025-01-27 Nat’l Multivar by Site*.html

NERR Region

The response matrix indicates that NERR Regions are significantly different (p=0.001). The Gulf Coast is different from all other regions while the Northeast is different from the Gulf Coast, Mid-Atlantic, and West Coast. While the Northeast region is not significantly different from the Southeast region, this does not mean they are the same.

Based on pairwise comparisons, using unadjusted p-values, the following groups are different from each other:

- Southeast and Gulf Coast (p = 0.003)
- Gulf Coast and Mid-Atlantic (p = 0.027)
- Gulf Coast and West Coast (p = 0.001)
- Gulf Coast and Northeast (p = 0.011)
- Mid-Atlantic and Northeast (p = 0.025)
- West Coast and Northeast (p = 0.001)

Salinity Category

The response matrix is significantly different by salinity category (p = 0.027), demonstrating that Oligohaline and Polyhaline sites are significantly different from each other (p = 0.031), but Mesohaline sites are not different from either other salinity category. This is consistent with Mesohaline being the intermediate salinity category.

Based on pairwise comparisons, using unadjusted p-values, the following groups are different from each other:

- Polyhaline vs. Oligohaline (p = 0.031)

Geomorphology

The response matrix is significantly different by geomorphology (p = 0.006), with Bay Front as the different geomorphology category. Riverine and Back Barriers were not significantly different.

Based on pairwise comparisons, using unadjusted p-values, the following groups are different from each other:

- Riverine vs. Bay Front (p = 0.017)
- Bay Front vs. Back barrier (p = 0.044)

Tidal Range

The response matrix is not significantly different by tidal range (p = 0.081).

Ordination - All sites

An NMDS was chosen to avoid PCA's assumption of multivariate normality. Additionally, the BIO-ENV procedure was created to help interpret NMDS ordinations.

BIO-ENV

BIO-ENV creates separate ordinations of the response matrix and the environmental matrix. It creates a matrix for each subset of environmental variables, and correlates each of these with the response matrix. The output identifies the subset of environmental variables showing the best correlation with the responses, which is a form of model selection.

With all sites included, the best model had 3 out of the 8 environmental variables: *Sea level rise over the previous 19 yrs; NERR Region; and Landscape resiliency condition*. The correlation between the response and environmental matrices was 0.336. The next-best correlation was 0.332 with the same three variables as above and the addition of *SET change minus SLR 19 yrs*. Correlations decreased as the environmental matrices got more complicated.

NMDS

With all sites included, the 2-dimensional stress was 0.038, which is excellent (Figure 23). The Gulf sites, particularly Grand Bay (GND) and Mission-Aransas (MAR), are noticeable outliers. EMI slope, SLR last 19 years, and landscape resiliency condition are particularly correlated with the outlying Gulf (primarily GND) sites. Richness and diversity are indistinguishable on the plot and appear higher in sites with less low marsh. This trend lines up with our ecological understanding of marshes as only a few species can tolerate the low marsh, indicating that as marshes shift into a greater proportion of low marsh, there are less species.

The total live vegetation slope is in an opposing direction than EMI slope. Conversely, the total unvegetated slope is in a similar direction to EMI slope, likely due to SLR having a similar effect as well as increasing bare/dead cover being a common category named in the creation of EMI.

Halophyte slope is in a similar direction as total live vegetation slope, which is unsurprising as it constitutes a large proportion of the total cover for many marshes. SET change minus SLR is essentially the opposite direction as SLR itself.

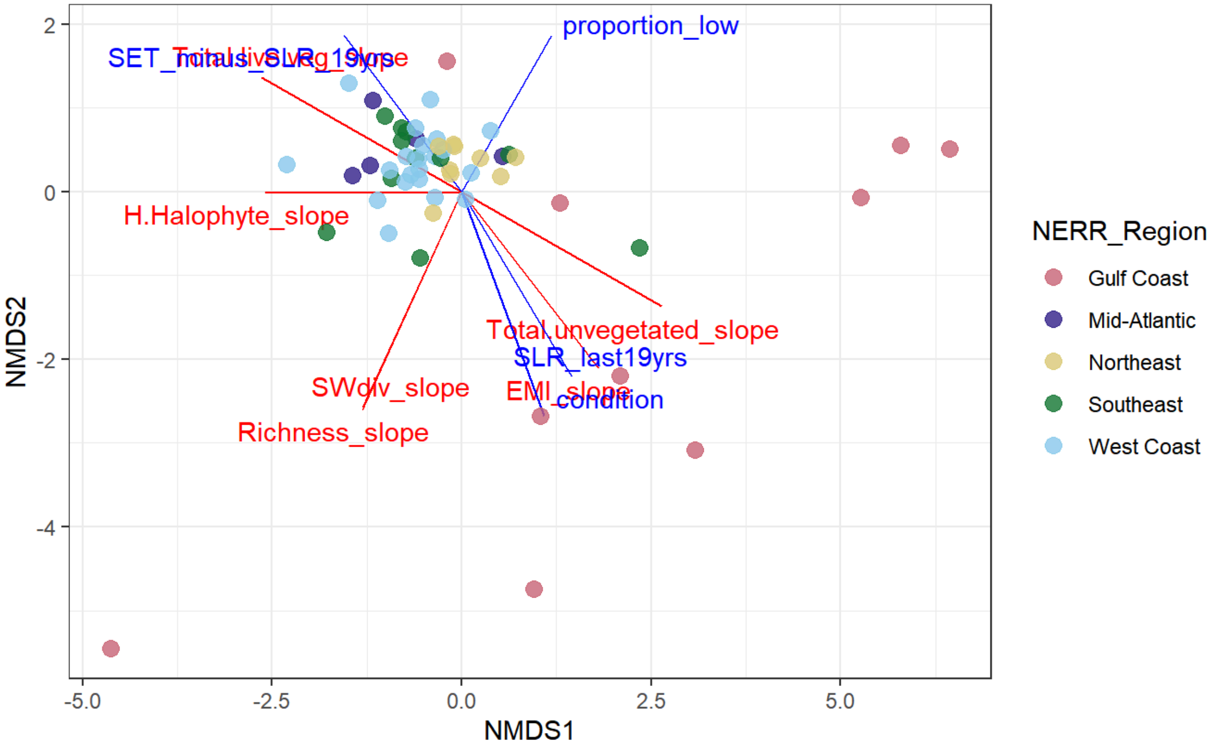


Figure 23: The NMDS plot of NERR sites showing all variables from the response matrix in red, all quantitative environmental variables from BIO-ENV in blue, and regions (also important according to BIO-ENV and PERMANOVA) as color. A few Gulf Coast sites are noticeable outliers.

<u>Ordination - Gulf sites removed</u>

Because the Gulf sites were outliers that could potentially be driving the multivariate analysis, BIO-ENV and NMDS were also run without them. This excluded sites from three Reserves: Appalachicola, Grand Bay, and Mission-Aransas.

BIO-ENV

The best BIO-ENV model also had 3 variables, but the only one in common with the analyses including all regions was *NERR Region* (Figure 24). The others were *Salinity category* and *proportion of the marsh that is low* (Figure 25; Figure 26). This correlation was worse than before with all regions, at only 0.130. The next-best correlation was 0.117, with those three variables and the addition of *SET change minus SLR*.

NMDS

Without the Gulf sites, stress was higher, but still good, at 0.097 (Figure 24). The same general direction is seen for the variables in the response matrix. Removing the Gulf sites changed the relationships between the response matrix, landscape resiliency condition, and proportion of low marsh. When quantitative environmental variables were overlaid, proportion of low marsh has flipped from pointing upwards to downwards and landscape resiliency condition has flipped from pointing down to pointing up. SLR changed slightly, but is still mostly in the same direction as with all regions.

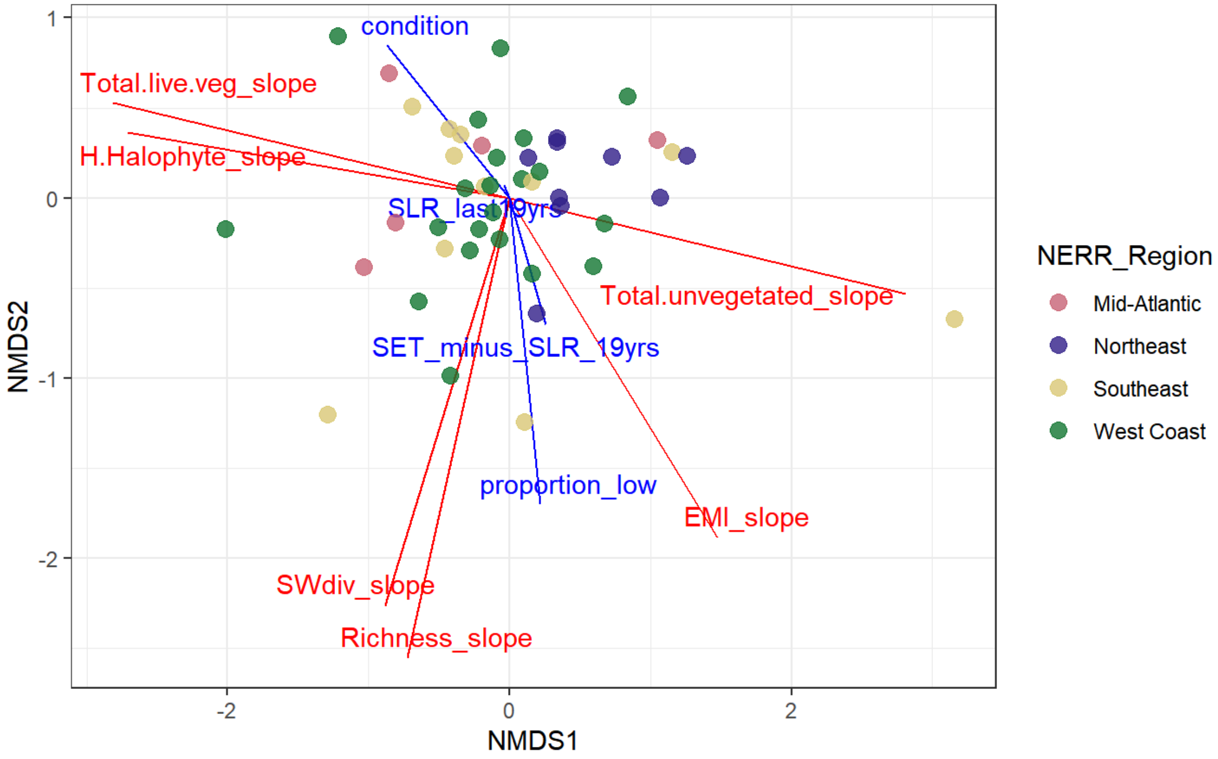


Figure 24: NMDS of all NERR sites <u>except</u> from Reserves located in the Gulf of Mexico region. The ordination is showing all variables from the response matrix in red, all quantitative environmental variables in blue, and regions (also important according to BIO-ENV and PERMANOVA) as color.

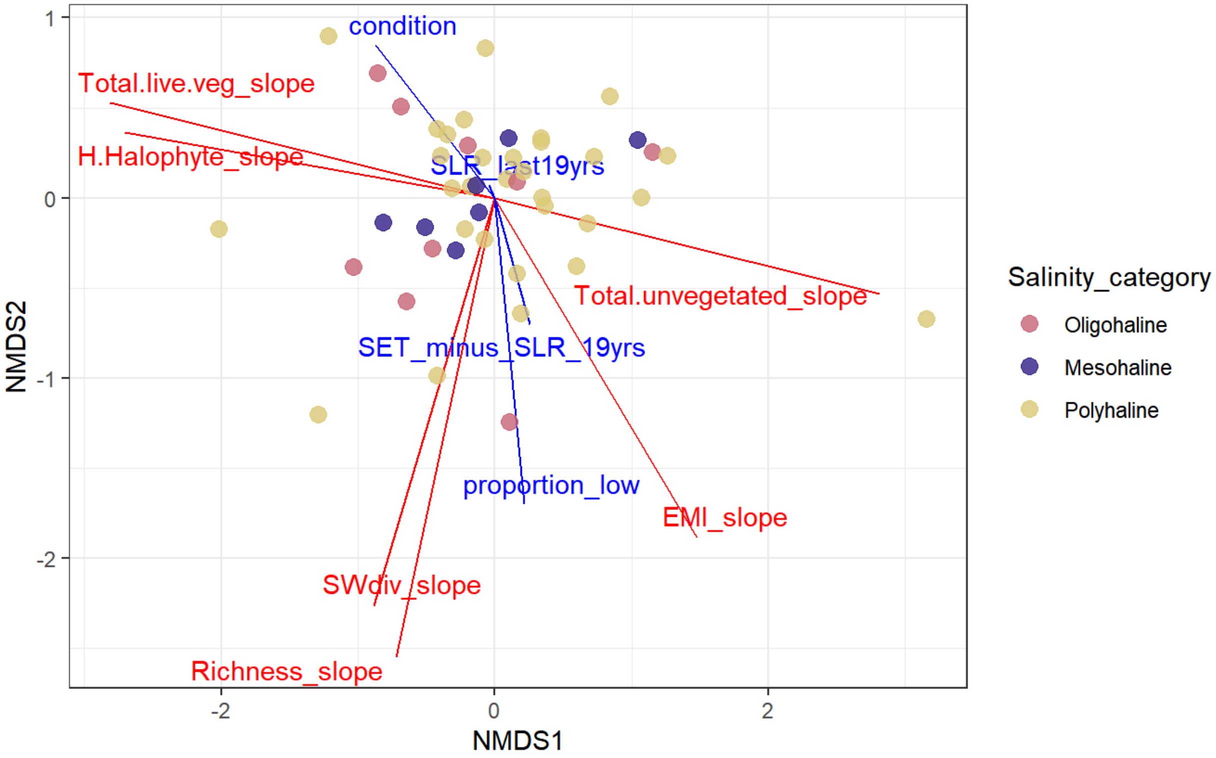


Figure 25: NMDS of all NERR sites except from Reserves located in the Gulf of Mexico region. The ordination is showing all variables from the response matrix in red, all quantitative environmental variables in blue, and salinity category (also important according to BIO-ENV and PERMANOVA) as color. Note that the mesohaline sites are in a fairly narrow ellipse in the middle of the plot while polyhaline sites have a generally large spread, depicting different dispersions amongst salinity groups.

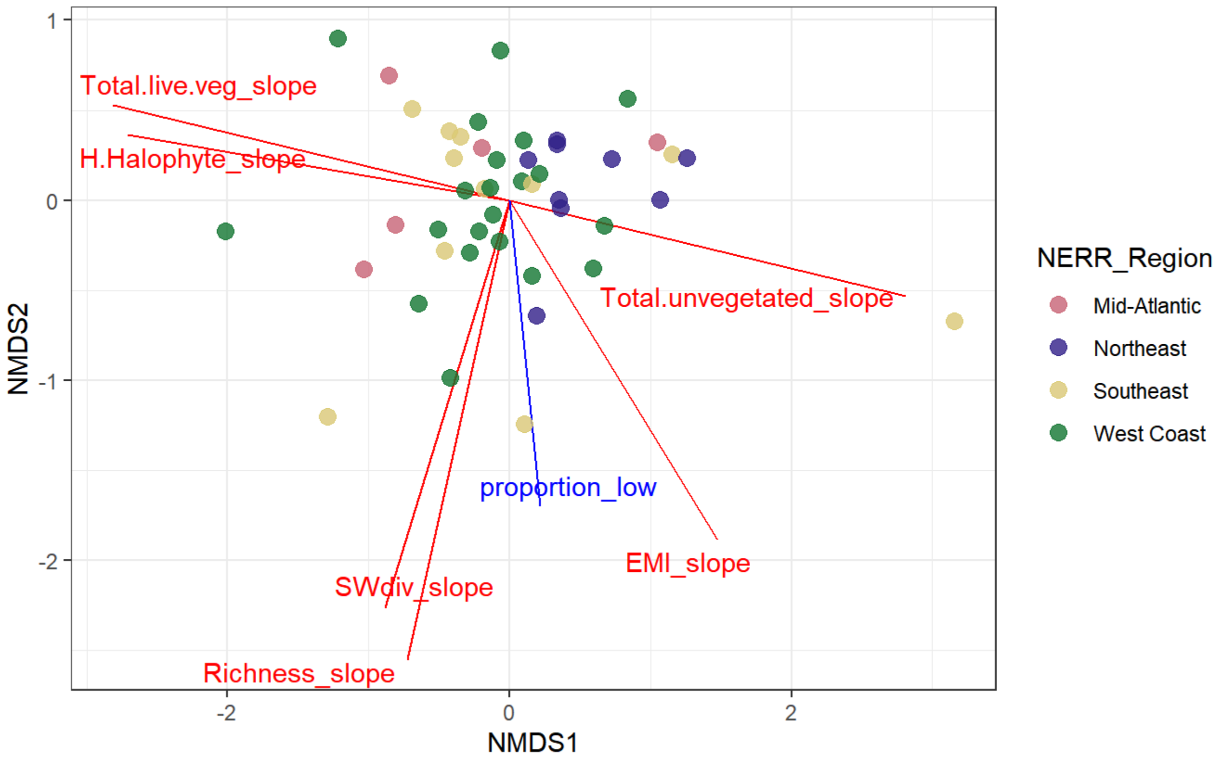


Figure 26. NMDS of all NERR sites <u>except</u> Reserves located in the Gulf of Mexico region. The ordination is showing all variables from the response matrix in red, only the best quantitative environmental variable from BIO-ENV in blue, and regions (also important according to BIO-ENV and PERMANOVA) as color. The PERMANOVA of sites from all regions indicated that the Gulf of Mexico and Northeast regions were different: here, the Northeast clusters around the x-axis on the right of the graph while other regions are more generally spread out, displaying dispersion differences amongst region groups.

<u>Ordination - Environmental Factors Only</u>

From the centered, scaled environmental predictor matrix, we made a matrix of the following continuous variables: *condition, Latitude, proportion_low, SET_change, SET_minus_SLR_19yrs, siteAvg_distance_to_water, siteAvg_orthometric_height, SLR_last19yrs*

An NMDS was then run using Euclidean distance, and the biplot points were colored by NERR region (region was not in the response matrix used to create the NMDS) (Figure 27). This figure shows regional differences in environmental variables and corresponds to the high multicollinearity seen between region and environmental variables in the LMEs.

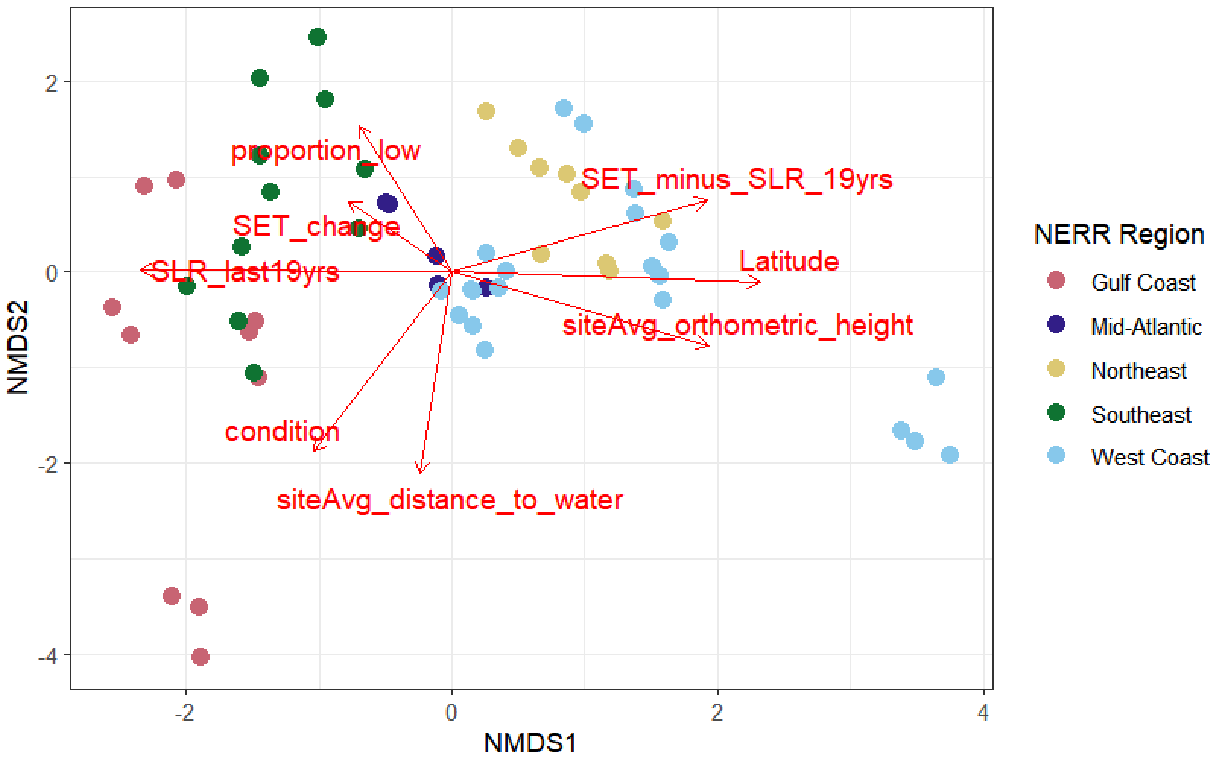


Figure 27: NMDS of all NERR sites color-coded by region, displaying a dispersal of NERR Regions across the x-axis. The ordination is showing all environmental variables from the response matrix in red. Stress is 0.11.

Resources

- Data Analysis
    - R coding for Univariate- Summary (Github), Univariate- LME Model Selection (R-files), and Multivariate (Github) analyses.
    - Dataframe dictionary
    - Data matrices
- Data Visualization Tools
    - Arc dashboard: User-friendly GIS application, displaying data layers associated with this project (e.g., plot waypoints, site descriptions, project results).
    - ArcGIS Reserve-Level and Site-Level Storymaps: User-friendly GIS application displaying trends in vegetation cover types (Halophyte, Live Cover, EMI) across Reserves
- Related Reports
    - Reserve-Level Analysis Methods and Results: companion analysis description, focused on the Reserve/site scale.

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Appendix: LME Summary Tables

LME1 best model summary

	Value	*Std. Error*	*DF*	*t-value*	*p-value*
(Intercept)	-0.04299446	0.014956442	21	-2.8746450	0.0091
Salinity_Cateogry Mesohaline	0.04227218	0.013760903	21	3.0719042	0.0058
Salinity_category Oligohaline	0.00464131	0.016077060	21	0.2886914	0.7756
Salinity_Category Polyhaline	0.03353310	0.012639501	21	2.6530396	0.0149
SLR_last19yrs	0.00337619	0.001186526	17	2.8454415	0.0112

LME2 simplest model summary

	Value	*Std. Error*	*DF*	*t-value*	*p-value*
Intercept	1.8778537	1.3578753	23	1.382935	0.1800
Intercept NERRS_Landscape_resiliencey_condition_sum_quantile	-0.5822812	0.2212274	23	-2.632048	0.0149

LME3 best model summary

	Value	*Std. Error*	*DF*	*t-value*	*p-value*
(Intercept)	-0.03133476	0.01250450	33	-2.505879	0.0173
Salinity_category Mesohaline	0.04128165	0.01258961	33	3.279027	0.0025
Salinity_category Oligohaline	0.01685420	0.01330969	33	1.266311	0.2143
Salinity_cateogry Polyhaline	0.03300885	0.01172846	33	2.814423	0.0082
SLR_last19yrs	0.00171935	0.00073331	20	2.344642	0.0295

LME4 best model summary

	Value	*Std. Error*	*DF*	*t-value*	*p-value*
(Intercept)	-2.883313	1.676834	32	-1.719499	0.0952
Salinity_category Mesohaline	2.237635	1.830540	32	1.222391	0.2305
Salinity_category Oligohaline	6.839405	2.142409	32	3.192391	0.0032
Salinity_category Polyhaline	3.362249	1.853102	32	1.814389	0.0790
proportion_low	-3.284855	1.317046	32	-2.494108	0.0180