Version of Record: https://www.sciencedirect.com/science/article/pii/S0006320716305742
Manuscript_28491bd095e6bb1023fff7461ab81a1b

Title: Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices

Running Head: Tidal marsh resilience to sea-level rise

Kenneth B. Raposa[a*]
Kerstin Wasson[b]
Erik Smith[c]
Jeffrey A. Crooks[d]
Patricia Delgado[e]
Sarah H. Fernald[f]
Matthew C. Ferner[g]
Alicia Helms[h]
Lyndie A. Hice[i]
Jordan W. Mora[j]
Brandon Puckett[k]
Denise Sanger[l]
Suzanne Shull[m]
Lindsay Spurrier[n]
Rachel Stevens[o]
Scott Lerberg[p]

[a] Narragansett Bay National Estuarine Research Reserve, 55 South Reserve Dr., Prudence Island, RI 02872, USA; kenny@nbnerr.org

[b] Elkhorn Slough National Estuarine Research Reserve, 1700 Elkhorn Road, Watsonville, CA 95076, USA; kerstin.wasson@gmail.com

[c] North Inlet-Winyah Bay National Estuarine Research Reserve, PO Box 1630, Georgetown, SC 29442, USA; erik@belle.baruch.sc.edu

[d] Tijuana River National Estuarine Research Reserve, 301 Caspian Way, Imperial Beach, CA 91932, USA; jcrooks@trnerr.org

[e] Jug Bay Wetlands Sanctuary, 1361 Wrighton Road, Lothian, MD 20711, USA; rpdelg88@aacounty.org

[f] Hudson River National Estuarine Research Reserve, 256 Norrie Point Way, P.O. Box 315, Staatsburg, NY 12580, USA; sarah.fernald@dec.ny.gov

[g] San Francisco Bay National Estuarine Research Reserve, 3152 Paradise Drive, Tiburon, CA 94920, USA; mferner@sfsu.edu

[h] South Slough National Estuarine Research Reserve, P.O. Box 5417, Charleston, OR 97420, USA; alicia.r.helms@state.or.us

[i] Delaware National Estuarine Research Reserve, 818 Kitts Hummock Road, Dover, DE 19901, USA; Lyndie.Hice-Dunton@state.de.us

[j] Waquoit Bay National Estuarine Research Reserve, 131 Waquoit Hwy, Woods Hole, MA 02536, USA; jordan.mora@state.ma.us

[k] North Carolina National Estuarine Research Reserve, 101 Pivers Island Rd., Beaufort, NC 28516, USA; Brandon.Puckett@ncdenr.gov

[l] ACE Basin National Estuarine Research Reserve, 217 Fort Johnson Road, Charleston, SC 29412, USA; SangerD@dnr.sc.gov

[m] Padilla Bay National Estuarine Research Reserve, 10441 Bayview-Edison Road, Mount Vernon, WA 98273, USA; sshull@padillabay.gov

[n] Grand Bay National Estuarine Research Reserve, Mississippi Department of Marine Resources, 6005 Bayou Heron Road, Moss Point, MS 39562, USA; Lindsay.Spurrier@dmr.ms.gov

[o] Great Bay National Estuarine Research Reserve, 89 Depot Rd, Greenland, NH 03840, USA; Rachel.Stevens@wildlife.nh.gov

[p] Chesapeake Bay National Estuarine Research Reserve of Virginia at the Virginia Institute of Marine Sciences, 1375 Greate Road., Gloucester Point, VA 23062, USA; lerbergs@vims.edu

* Corresponding author
Phone: 401.683.7849
Fax: 401.683.7366
Email: Kenny@nbnerr.org

Type of paper: Full length research paper

Abstract

Tidal marshes and the ecosystem services they provide may be at risk from sea-level rise (SLR). Tidal marsh resilience to SLR can vary due to differences in local rates of SLR, geomorphology, sediment availability and other factors. Understanding differences in resilience is critical to inform coastal management and policy, but comparing resilience across marshes is hindered by a lack of simple, effective analysis tools. Quantitative, multi-metric indices are widely employed to inform management of benthic aquatic ecosystems, but not coastal wetlands. Here, we develop and apply tidal marsh resilience to sea-level rise (MARS) indices incorporating ten metrics that contribute to overall marsh resilience to SLR. We applied MARS indices to tidal marshes at 16 National Estuarine Research Reserves across the conterminous U.S. This assessment revealed moderate resilience overall, although nearly all marshes had some indication of risk. Pacific marshes were generally more resilient to SLR than Atlantic ones, with the least resilient marshes found in southern New England. We provide a calculation tool to facilitate application of the MARS indices to additional marshes. MARS index scores can inform the choice of the most appropriate coastal management strategy for a marsh: moderate scores call for actions to enhance resilience while low scores suggest investment may be better directed to adaptation strategies such as creating opportunities for marsh migration rather than attempting to save existing marshes. The MARS indices thus provide a powerful new approach to evaluate tidal marsh resilience and to inform development of adaptation strategies in the face of SLR.

Keywords: assessment, index, marsh, National Estuarine Research Reserve System (NERRS), resilience, sea-level rise

1. Introduction

Tidal marshes are among the most productive ecosystems on earth, and provide key services including shoreline protection, water quality improvement, provision of fish habitat (Gedan et al., 2009), and carbon sequestration (McLeod et al., 2011). Coastal wetlands are naturally dynamic, expanding and contracting in extent in response to altered river flow and tidal dynamics, but many extensive tidal marshes have persisted for millennia (Redfield, 1972). Marsh condition and extent are influenced by many abiotic and biotic factors, which are variable across time and space, but in some systems have been altered by humans beyond the natural range of variability. For instance, river diversion can decrease freshwater inputs and lead to declines in inorganic sediment supply and organic soil building (Day et al., 2008), eutrophication can harm marsh integrity (Deegan et al., 2012; Watson et al., 2014), and runaway herbivory can result in marsh dieback (Silliman et al., 2005; Holdredge et al., 2009). The impacts of these factors are now being compounded by additional impacts from climate change, including changes to temperature and precipitation (Osland et al., 2016).

One major emerging threat to marsh stability and function is the projected acceleration in the rate of sea-level rise (SLR) (Kirwan & Megonigal, 2013). Tidal marshes occupy a narrow elevational range, where wetland plants drown if inundated excessively and are replaced by upland species if inundated insufficiently. In the face of past SLR, many marshes have been able to maintain their relative position in the tidal frame, but this resilience requires sufficient inorganic sediment supply or organic soil building to allow marsh elevation to track rising water levels over time (Morris et al., 2002; Kirwan & Megonigal, 2013). In the coming century, SLR is projected to accelerate dramatically over rates documented for the past millennia, though there is a high degree of uncertainty about the magnitude of future rates (Nicholls & Cazenave, 2010; Rahmstorf, 2010; Hansen et al., 2016). Coastal wetlands will persist in their current locations only if they can continue to build vertically at a rate equal to or greater than this accelerated rate of SLR. Their ability to do so may be hampered by human alterations, such as decreased riverine sediment supply or increased subsidence rates (Morris et al., 2002; Day et al., 2008; Kirwan & Megonigal, 2013). Alternatively, some coastal wetlands may migrate to new, higher positions in the landscape, though this is not possible in many regions due to built structures and urban development. There is therefore concern that SLR may lead to significant loss of tidal marshes and the key ecosystem services they provide (Craft et al., 2009), though recent analyses suggest that marsh vulnerability to SLR may be overestimated (Kirwan et al., 2016).

Not all coastal wetlands will be equally affected by accelerated SLR (Day et al., 2008). Tidal marsh responses will not be uniform due to differences in <u>sensitivity</u>. In part, sensitivity can vary due to natural differences across sites, such as tidal range or proximity to riverine sediment sources. Indeed, these two factors – tidal range and sediment supply – are considered critical indicators of marsh sensitivity to accelerated SLR (Kirwan et al., 2010; Fagherazzi et al., 2012). Sensitivity to SLR can also be affected by prior human alterations that degraded marsh integrity. For instance, marshes in which vegetation is low in the tidal frame due to subsidence induced by eutrophication (Deegan et al., 2012) or decreased sediment supply are particularly vulnerable to increased rates of SLR (Morris et al., 2002; Cahoon & Guntenspergen, 2010). In addition to variation in sensitivity, there also will be regional oceanographic differences and local hydrodynamic factors that can lead to site-specific differences in <u>exposure</u> to accelerated SLR (Sallenger et al., 2012).

In order to inform coastal management and policy, it is critical to characterize marsh resilience to accelerated SLR across multiple spatial scales. Assessments of the relative vulnerability of wetlands have not occurred for most regions of the world, and yet are critical to prioritize restoration investment in wetlands and identify appropriate management strategies (Webb et al., 2013). At a national scale, assessments could shape policy and investments. At a local scale, understanding a marsh's resilience may lead to implementation of the most appropriate management actions, such as restoration intervention to enhance resilience vs. investment in opportunities for marsh migration where existing marshes have little chance of persisting. Tools to quantify marsh resilience in the face of SLR are thus urgently needed (Cahoon & Guntenspergen, 2010).

One approach to characterizing marsh resilience is the development and application of numerical models. A variety of these have been generated, ranging in geographic scope from single points to entire landscapes, and incorporating only a few physical variables vs. building in complex biological feedbacks (Fagherazzi et al., 2012). Most models have been used to examine a single marsh or estuary, with the purpose of making detailed spatial predictions for the region of interest. For instance, Schile et al. (2014) recently applied sophisticated models incorporating ecological feedbacks to projections for resilience of four marshes in San Francisco Bay, CA. Models are also very well suited for exploring hypotheses about marsh processes and for exploring different future scenarios of SLR rates or sediment concentrations (Kirwan et al., 2010; Kirwan et al., 2016).

Another potential approach to characterizing marsh resilience is the use of an integrative multi-metric index. Quantitative, multi-metric evaluations of habitat quality developed specifically to inform management are commonly used to assess and compare benthic aquatic ecosystems (Diaz et al., 2004; Pinto et al., 2009). The purpose of these indices is to assign a score that reflects current conditions, which differs from the spatially-explicit predictions that are typical of numerical models. These indices typically integrate a suite of complementary metrics into a combined overall score for each site. The indices can be applied consistently at different spatial scales, allowing for relative comparisons and prioritization for management action. Although benthic habitat quality indices are widely considered to be useful tools for decision-making in aquatic management and policy (Pinto et al., 2009), only recently have multi-metric indices been applied to wetland vegetation (Miller et al., 2016), and this approach has not yet been applied to assessments of coastal wetland resilience.

Our goal was therefore to develop and apply the first set of integrative indices to quantify marsh resilience in the face of SLR. We selected multiple metrics that have been identified in the literature as reflecting both <u>sensitivity</u> and <u>exposure</u> of marshes to SLR and used these to develop three different resilience indices. The focus of the indices is on existing environmental conditions that affect marsh resilience. This differs from a typical numerical model because the output is not a spatial or temporal prediction of how the marsh will change in a particular time period under scenarios of SLR, but rather is a simple integrative assessment of site characteristics that influence resilience. The indices can be used to compare among marshes at any geographic scale. An explicit objective was to develop a method that could be used by any scientist or organization collecting the relevant monitoring data, and that is transparent for coastal managers to understand. As shorthand, we refer to these as MARS indices, assessing tidal <u>ma</u>rsh <u>r</u>esilience to <u>s</u>ea-level rise. We use the term "resilience" as it has been developed in the ecological literature to indicate the ability of a system to resist and recover from perturbation (Holling, 1973; Gunderson, 2000). Alternatively, we could have used the inverse term, "vulnerability", but this often includes an assessment of adaptive capacity and socioeconomic components that are not currently included in our indices. Although they have been developed separately by ecological vs. socioeconomic practitioners, it is clear that resilience and vulnerability are complementary concepts that merit better integration (Miller et al., 2010). While some multi-metric indices assess existing responses (e.g., of invertebrate communities) to a known gradient of human disturbance (e.g., pollution levels), our indices emphasize conditions that are likely to affect future marsh resilience to a projected disturbance (SLR). We therefore cannot ground truth which metrics serve as best indicators, but rather apply the "universal metric approach" (Schoolmaster et al., 2012), drawing on indicators of ecological integrity previously identified as critical by expert judgment or in the published literature.

We applied the new MARS indices to characterize and compare resilience at 16 tidal marshes in six biogeographic regions across the conterminous U.S. Scaling up, this allowed us to provide an overall snapshot of marsh resilience across the nation, as well as to identify some specific marshes at greatest risk. To accomplish this, we drew on data collected consistently as part of the National Estuarine Research Reserve (NERR) System-wide Monitoring Program (SWMP), which develops and implements robust, vetted protocols for collecting and processing monitoring data in U.S. estuaries (Buskey et al., 2015; http://cdmo.baruch.sc.edu/). The reserves have invested heavily in monitoring that will allow them to function as "sentinel sites" for coastal wetland response to SLR, and thus serve as an ideal platform for conducting national syntheses of estuarine conditions and responses to stressors (NERRS, 2012). This addresses a critical need for coordinated networks to monitor wetland elevation changes and responses to SLR (Webb et al., 2013). To our knowledge, ours is the first attempt to characterize marsh resilience in the face of SLR at a continental scale and to examine geographic patterns of variation.

2. Materials and methods

2.1. Study sites

This study was conducted in tidal marshes located in or near 16 NERRs distributed across the conterminous U.S. (Fig. 1). Participating reserves are located in six NERR biogeographic regions that are based largely on flora, fauna, and climate. These regions include the Acadian (Maine to New Hampshire; one reserve), Virginian (Massachusetts to Virginia; six reserves), Carolinian (North Carolina to northeast Florida; three reserves), Louisianan (Alabama to Texas; one reserve), Columbian (Washington to Oregon; two reserves), and Californian (California; three reserves) (Table A1). Hereafter, we use the terms "biogeographic region" and "region" interchangeably. In a few instances, we also refer to more colloquial geographic areas such as 'Pacific Coast' and 'southern New England' when patterns emerged at scales different from those represented by the NERR biogeographic regions. To assess regional and national patterns in tidal marsh resilience to SLR, we included data from one marsh from each participating reserve (currently, robust datasets relevant to our study are only available from one marsh at most reserves). However, to examine how resilience varies among marshes within the same NERR or estuary we also included additional marshes from the Narragansett Bay RI, Hudson River NY, and Elkhorn Slough CA reserves in a separate analysis of local variation.

Marshes varied considerably in size, geomorphology, salinity, and vegetation. In some estuaries (e.g., Narragansett Bay RI, Padilla Bay WA), marshes were relatively small, discrete pocket or fringe marshes, while in others (e.g., Chesapeake Bay MD, North Inlet SC) the marshes are small subsections of much larger contiguous marsh systems. In still other estuaries (e.g., Elkhorn Slough CA, Tijuana River CA), data were collected from various marsh locations that essentially represent the entire extent of marshes throughout these relatively small estuaries. This variability is in part a reflection of reserves focusing on different areas of interest that depend on local needs. In most cases, sampling was not designed for scaling up to a larger geographic area; instead it aims to reflect conditions in that particular marsh or marsh area of interest.

Our study focuses on salt marshes, which were sampled at 14 of the 16 NERRs, but also includes tidal freshwater marshes in the Hudson River NY and Chesapeake Bay MD NERRs (Table A1). Dominant vegetation species varied considerably among marsh types, reserves and regions, but in general *Spartina* spp. dominated most Atlantic Coast salt marshes while *Spartina foliosa* and *Salicornia pacifica* were common on the Pacific Coast. The selection of marshes from across the NERRS ensured that our initial application of the MARS indices would span a diverse set of tidal marshes in a variety of estuarine settings over a broad spatial scale.

2.2. Metrics

We used ten individual metrics, grouped into five broader categories (Table 1), to calculate three indices of marsh resilience to SLR. The overarching rationale was to develop indices based on multiple metrics evaluating marsh resilience to SLR and to select metrics that reflect recent conditions (e.g., the past decade) in order to project marsh resilience forward in the near-term. The categories and metrics include: 1) marsh elevation distribution (percent of marsh below local mean high water [MHW], percent of marsh in the lower third of overall plant distribution, skewness); 2) marsh elevation change over time; 3) accretion and sediments (short-term accretion from marker horizons, long-term accretion from radiometric dating of soil cores, turbidity); 4) tidal range; and 5) sea-level rise (long-term rate, short-term variability). Individually, each metric provides an incomplete assessment of marsh resilience, but collectively the metrics provide an integrated assessment of overall marsh resilience to SLR. Below, we briefly explain the rationale for including each category and metric in our assessment and describe basic field methods for collecting the required data for each metric (additional information is provided in Table A2).

Within the marsh elevation distribution category, we included three complementary metrics that reflect different aspects of marsh resilience. The rationale for including these metrics is that marshes predominantly distributed low in the local tidal frame or within their overall distributional range are likely less resilient to SLR (Morris et al., 2002). The first metric is the percentage of marsh elevation points below local MHW. This is simply a reflection that the distribution and zonation of marsh plants is often strongly related to flooding tolerance and, therefore, to local tidal datums (Lefor et al., 1987; Morris et al., 2002). Data requirements include a robust set of recent elevation points (e.g., from real-time kinematic GPS surveys) distributed over the entire elevational range of the marsh plants at each site and an estimate of the elevation of MHW that is relevant to the study marsh. One benefit of this metric is that it is always relative to the same tidal datum (i.e., MHW), thereby facilitating consistent comparisons among sites. Conversely, comparisons of this metric among disparate sites can be misleading when marshes have vegetation species with different flooding tolerances (e.g., *Spartina* *alterniflora* is relatively tolerant of tidal flooding and is often found below MHW, while *Salicornia* spp. are intolerant of extended submergence and generally found above MHW).

To account for variations in flooding tolerance among plant species, we also included a metric that reflects the distribution of marsh elevations relative to observed plant tolerance at a site (i.e., percent of marsh elevations in the lower third of overall plant distribution). For example, a marsh that has vegetation at elevations ranging from 0.5 m to 2.0 m above mean lower low water (MLLW) and 75% of measured elevation points in the lower third of that range (i.e., below 1.0 m) should be less resilient than a marsh with the same elevation range but with only 10% of its elevation points below 1.0 m. Our selection of the lower third of plant distribution range was arbitrary; the specific cutoff does not matter as long as it is consistent among all sites. A benefit of this metric is that it only requires determining the entire range of elevations that support marsh plants at each site; a local tidal datum does not need to be calculated because this is an ecologically-relevant metric based on observed plant tolerance.

The last metric included in the marsh elevation distribution category is skewness, which is based on previous work relating marsh elevation distributions to marsh vulnerability to SLR (Morris et al., 2005). Positive skewness values (a right-skewed distribution) indicate that the distribution of vegetation is clustered towards lower elevations and is likely more susceptible to drowning. Negative numbers (a left-skewed distribution) indicate that the distribution of vegetation is clustered towards higher elevations, which should make the marsh more resilient to SLR. Benefits of this metric are that it does not require calculating a tidal datum and that it applies across plant species with different elevation ranges.

The rate at which a marsh increases in elevation over time is another indicator of how resilient a marsh is to SLR. The importance of this indicator is reflected in calls for expanding the global network of surface elevation tables (SETs) to quantify rates of marsh elevation change over broad spatial scales (Webb et al., 2013). Our second category is comprised of a single metric that is simply the rate of marsh elevation change over time. This rate can be positive or negative and is derived from time-series data collected from one or more SETs at each marsh (in our study, averages were calculated for marshes that had multiple SETs at different elevations). Ideally, this metric should be calculated from enough years of data to understand longer-term processes (e.g., 10+ years) and from multiple SETs covering the full range of marsh elevations, but for this analysis we included data from shorter periods for those reserves that only installed SETs more recently, or from a small number of SETs where spatial coverage remains limited (Table A2). It is also ideal to make comparisons of elevation change rates among marshes using data from SETs located in the same habitat or at similar elevations relative to local tidal datums (e.g., in low marsh habitat or near mean high water; Kirwan, 2016). This was not always possible in our initial analysis because many reserves only have a small number of relatively new SETs that were located in areas defined by local needs.

The rate of marsh elevation change is the net result of multiple surface and subsurface processes, including deposition of sediments at the surface and accumulation of organic material below the surface. We therefore included a category with metrics related to accretion and sediment supply, since marshes with high accretion rates should be generally more resilient to SLR. The short-term accretion rate metric focuses on surface accretion of sediments, and is simply calculated using time-series data from marker horizons that are typically associated with SETs. The short-term time period varied in our study for reasons stated above for SETs (Table A2), but was generally from within the most recent ten-year period. Because short-term accretion data were not available from multiple reserves, we also included the long-term accretion rate in this initial analysis. Long-term accretion rate encompasses both surface and subsurface accumulation of organic and inorganic material, and is derived from radiometric dating of one or more soil cores at each marsh. Again, the time period covered by this metric varied across reserves, but generally reflected accretion rates over the last 30 to 50 years (for many reserves, accretion data from cores is available for much longer time periods, but we focused on the more recent decades as identified by markers such as radioactive isotopes of lead and cesium).

We included a third metric in this category to reflect suspended sediment concentrations in the water column adjacent to each marsh, as a proxy for sediment supply. Suspended sediment concentrations are recognized as critical for predicting marsh resilience to SLR (Fagherazzi et al., 2012), although examination of the differential between flooding and ebbing tides may be the best indicator (Ganju et al., 2015). As a part of SWMP water quality monitoring, all NERRs collect continuous water column <u>turbidity</u> (NTU) measurements, so we used this as the metric for our assessment. The turbidity metric is calculated by taking the mean turbidity value from a local SWMP station in or near each marsh over five recent years (2009 to 2014). However, we recognize that turbidity measurements may not be available at other sites where the MARS indices might be applied in the future and researchers may instead have direct measurements of total suspended solids (TSS). We therefore examined the relationship between turbidity and TSS with data from 11 reserves that collect both types of data. We used this relationship to develop an alternative sediment metric using TSS in lieu of turbidity, and other studies have shown correlations between these two metrics (Grayson et al., 1996; Packman et al., 1999).

Marshes subject to a higher range of tides generally have a correspondingly broad range in elevations supporting marsh plants, which should increase resilience to SLR (Fagherazzi et al., 2012). For example, a 20-cm rise in sea-level will be much more likely to drown a marsh that has a 30-cm tidal range than one with a 200-cm tidal range. We therefore include <u>tidal range</u> as a category and metric. This is calculated using time-series data from a SWMP station (or similar tide station) in or near each marsh and averaging the mean daily difference in water levels (i.e., highest daily water level minus lowest daily water level) across a recent time period (2009 to 2014 in our study).

Finally, marshes that are exposed to high rates of SLR are in greater danger of drowning than marshes subject to lower rates. In the SLR category, we include a metric for the <u>long-term rate of SLR</u> and another that reflects recent <u>short-term, inter-annual variability in water levels</u>. The former metric is the published rate of change in mean sea-level (MSL) from the nearest or most appropriate National Water Level Observation Network (NWLON) station for each marsh (tidesandcurrents.noaa.gov). The latter metric is calculated from the same NWLON station; it is the mean monthly water level anomaly over the last 10 years after accounting for seasonal cycles and the long-term trend (e.g., a high value reflects relatively high water levels in the local area during that time period). A benefit to using these metrics is that they reflect patterns in water levels over multiple time-periods using robust datasets from a coordinated network of long-term tide stations that are easily accessible and publicly available.

2.3. Scoring and MARS indices

We first scored the values for each individual metric. Each measurement was assigned a score of 1 to 5, where 1 represents lowest resilience to SLR and 5 the highest (for ease of visualization, we assigned colors from red to green with these scores; Table 2). We defined the range of data values associated with each score for each metric. To assign these score definitions, we examined the range of variation of data across all 16 NERR marshes. We omitted extreme outlier values, and then broke the data ranges into evenly-spaced categories. For metrics such as marsh elevation change, we also ensured that scores were consistent with an understanding of marsh processes, for instance with marshes that are not currently tracking local long-term SLR receiving low scores. For other metrics such as turbidity, we had no a priori basis for score assignments and simply used categories that encompassed the spread of the data (minus outliers). Once all individual metrics were scored, mean scores were calculated for each broader category that contained more than one metric (metric and category scores were identical for categories with only one metric; e.g., tidal range).

The MARS risk index was based on the concept that a low score for any of the five categories represents a risk in the face of SLR and multiple low scores represent higher risk. Conversely, high category scores represent low risk. We calculated the risk index by summing the number of categories that scored moderate to high (defined as having a mean category score of ≥ 3), representing low risk. As an example, if a mean score of ≥ 3 was obtained for the 'marsh elevation change' and 'SLR' categories, but not the other three categories, that marsh would receive a MARS risk index score of 2. The MARS average index was simply calculated by taking the average of the five category scores. The MARS ratio index was calculated by dividing the rate of marsh elevation change by the long-term rate of SLR.

Since these are new indices, we were interested in exploring relationships among metrics and indices. We therefore used Spearman Rank Order Correlations (in SigmaPlot version 12.0) to test for relationships among the three MARS indices, and between all pairs of scoring metrics that are in the same category.

2.4. Regional and local patterns

To explore patterns in resilience across broad geographic scales, index scores were averaged among marshes within each biogeographic region. To complement the index scoring, we also used a series of analyses to explore broad-scale patterns in marsh resilience based on our multi-metric datasets. Non-metric Multi-Dimensional Scaling (nMDS) was used to arrange sites in two-dimensional space based on similarity in the suite of resilience metrics. Analysis of Similarity (ANOSIM) was then used to test for significant differences in resilience among marshes in different biogeographic regions. Because all the metrics are based on disparate types of data, all data were normalized prior to all multivariate analyses. Resemblance matrices were developed based on Euclidean distance among samples prior to all ANOSIM and nMDS analyses. All analyses were conducted using PRIMER version 7 (Clarke et al., 2014).

In order to explore how resilience varies locally (i.e., within an estuary), we also compiled data and calculated MARS indices for additional marshes at the Narragansett Bay RI, Hudson River NY, and Elkhorn Slough CA reserves (replicate marshes within each reserve were all in relatively close proximity to one another i.e., less than 10 km apart). We then compared the degree of variability in resilience across multiple spatial scales by calculating coefficients of variation (CV) at local, regional, and national scales. Finally, we performed a second nMDS analysis that included all the primary marshes as well as the additional local marshes.

3. Results

3.1. Marsh elevation distribution

Marsh elevation distribution was highly variable across the 16 marshes (Table 3). The percent of marsh elevations below MHW ranged from 0 to 84%, and the percent of marsh elevations in the lowest third of plant distribution ranged from 4 to 85%. However, results for these two particular metrics were not consistent among marshes in different regions. For example, a number of Atlantic Coast marshes had a higher percentage of their elevations below MHW and scored correspondingly low on this metric. In contrast, some Pacific Coast marshes had proportionally more of their elevations in the lower third of the observed range in plant distribution and scored lower on the plant tolerance metric. The contrasting results based on different elevation distribution metrics is illustrated using data from Narragansett Bay RI and Tijuana River CA (Fig. 2). In this example, the marsh in Narragansett Bay scores low when using only the percent below MHW metric, while the marsh in Tijuana River scores low on the plant tolerance and skewness metrics.

3.2. Marsh elevation change over time

Dramatic differences were also seen among marshes when examining the elevation change metric (Table 3). Some marshes are gaining elevation at relatively high rates (Hudson River NY and Tijuana River CA), while others are gaining much more slowly (Waquoit Bay MA, Narragansett Bay RI, and Elkhorn Slough CA) or are experiencing elevation declines (North Carolina and South Slough OR). Rates of elevation change were generally not consistent within marsh type (e.g., the two freshwater marshes in Hudson River NH and Chesapeake Bay MD had very different rates) nor biogeographic region (e.g., rates varied widely within the Virginian and Californian regions).

3.3. Accretion and sediment supply

Spatial patterns in accretion could not be thoroughly characterized because of the limited number of sites with robust accretion datasets. However, of the 11 marshes with both short-term accretion and elevation change data, about half (45%) have elevation change rates lower than accretion rates (Table 3), suggesting that increases in marsh elevation due to accretion are being partially offset by shallow subsidence at these marshes. Long-term accretion rates were very similar to short-term rates at five marshes (Narragansett Bay RI, Delaware, South Slough OR, San Francisco Bay CA, and Elkhorn Slough CA) but substantially lower at two other marshes (Hudson River NY and Chesapeake Bay MD).

Mean turbidity also varied markedly among sites, ranging from 2 to 61 NTU, with no apparent patterns among regions. Our examination of the relationship between turbidity and TSS across 11 sites revealed a remarkably strong relationship (Fig. 3). When comparing across sites, these currencies are very highly correlated and can be used almost interchangeably.

3.4. Tidal range and sea-level rise

Resilience metrics related to tidal range and sea-level rise varied dramatically among marshes over broad spatial scales (Table 3). For example, tidal range was markedly higher at high-latitude marshes (e.g., Great Bay NH, Padilla Bay WA) compared to low latitude (e.g., Grand Bay MS) and back-barrier (e.g., Nag Marsh in Narragansett Bay RI and Sage Lot Pond

Marsh in Waquoit Bay MA) marshes. The long-term rate of SLR ranged from 0.8 to 4.6 mm per year among sites and was generally lower along the Pacific Coast and higher in the Virginian region. Similarly, Virginian marshes have also been exposed to higher water levels in recent years relative to long-term conditions (i.e., high values for the short-term water level variability metric), while some southeastern and Pacific Coast marshes have been experiencing lower water levels compared to long-term conditions.

3.5. MARS indices

Scores among marshes and regions varied among the three indices, but some general patterns emerged. Based on the MARS risk index, many marshes are moderately resilient to SLR (i.e., 7 of 16 marshes had 2 or 3 categories classified as low risk) (Table 3); the mean score across the 16 marshes was 3.1 out of a maximum of 5. The two southern New England marshes (Narragansett Bay RI and Waquoit Bay MA) were the least resilient based on this index (i.e., each scored 1), but there was no apparent spatial pattern among the remaining seven marshes with relatively high resilience scores of 4 or 5.

Scores were even more similar among marshes based on the MARS average index (potential range of 1 to 5). In this case, 13 out of 16 marshes scored as moderately resilient (i.e., scores between 2 and 4), with a mean score across all marshes of 3.0. Interestingly, the three New England marshes scored at opposite ends of the overall range; Great Bay NH scored as highly resilient (i.e., > 4), while the marshes in RI and MA once again received the lowest resilience scores based on this index (i.e., < 2).

Most marshes appear less resilient to SLR based on MARS ratio scores (mean score of 1.2) than the other MARS indices. The marshes in North Carolina and South Slough OR had negative MARS ratio scores due to declines in marsh elevation over time (i.e., very low resilience), whereas six additional marshes across three regions (Table 3) had ratios that were less than 1, indicating that these marshes are also not gaining elevation at rates commensurate with SLR. Four marshes had ratio scores between 1 and 2, and three marshes (Great Bay NH, Hudson River NY, and Tijuana River CA) had ratios higher than 2 indicating very high resilience to SLR based on this index.

Scores on the three resilience indices were significantly correlated with each other (correlation coefficient = 0.81, $P < 0.0001$ for the risk and average indices; correlation coefficient = 0.58, $P = 0.02$ for the risk and ratio indices; correlation coefficient = 0.61, $P = 0.01$ for the average and ratio indices), which suggests that each index is reflecting the same pattern in relative marsh resilience across sites at the national scale. In contrast, only two pairs of metrics within the same category were significantly correlated with each other (correlation coefficient = 0.82, $P = 0.01$ for short and long-term accretion; correlation coefficient = 0.67, $P = 0.006$ for long-term SLR and short-term water level variability; $P > 0.05$ for all other pairs tested). The lack of correlations among most metrics demonstrates that each metric reflects a different component of overall marsh resilience to SLR and that redundancy among metrics in our study was minimal.

3.6. Regional patterns

Regional patterns emerged from our analysis, despite limited numbers of marshes within each region. Acadian and Californian marshes were consistently identified as most resilient based on mean index scores (Fig. 4). Clear regional groupings also emerged based on nMDS, which suggests that the degree to which a given marsh is resilient to SLR is partly driven by regional patterns of sensitivity and/or exposure as expressed by the ten metrics (Fig. 5). ANOSIM revealed a marginally significant difference in resilience metrics among regions (Global R = 0.224, P = 0.089). Post-hoc pair-wise comparisons showed that Virginian marshes were significantly different from both Columbian (R = 0.76, p = 0.036) and Californian marshes (R = 0.41, P = 0.048); differences between all other pairs of regions were not significant (P > 0.05 in each case). These findings are supported by an ANOSIM that only includes data from regions with at least three replicate marshes (i.e., by dropping the lone Acadian and Louisianan marshes and by combining the Columbian and Californian marshes into one broader Pacific group). In this ANOSIM with larger sample sizes (Global R = 0.291, P = 0.016), there was a significant difference between Virginian and Pacific marshes (R = 0.53, P = 0.002), but not between Virginian and Carolinian, nor between Carolinian and Pacific (P > 0.05 in both cases). In the future, further replication of marshes within different regions could shed more light on regional trends; our limited replication allows for only a preliminary characterization of some regions, and we cannot generalize about the Acadian and Louisianan regions with just one marsh sampled in each.

3.7. Local variation

Resilience to SLR was fairly similar among marshes within the same estuary based on scores from additional marshes in Narragansett Bay RI, Hudson River NY, and Elkhorn Slough CA (Table 4). Among the three indices, the MARS ratio index was the most variable locally, particularly in Hudson River. Coefficients of variation and MARS average index scores showed markedly lower within-estuary variability in marsh resilience (mean CV = 0.05) than variability at regional (mean CV = 0.15) and national scales (overall CV = 0.23). An nMDS analysis revealed that local marshes clustered closely together in Narragansett Bay RI and Elkhorn Slough CA, indicative of similarities among the resilience metrics, but not in Hudson River NY (Fig. A1).

4. Discussion

4.1. Integrated approach to assessing marsh resilience to SLR

In this study, we have developed and applied the MARS indices, providing for the first time a robust, integrated multi-metric assessment of marsh resilience to SLR. These indices can be applied at various geographic scales by any researcher or organization with the appropriate datasets, and may be particularly applicable to networks of marsh sites such as U.S. Fish and Wildlife Service refuges, or coordinated agency monitoring such as that conducted by the U.S. Geological Survey and NOAA Sentinel Site Cooperatives. The indices allow for consistent comparisons among coastal wetlands, and address a critical need to assess relative wetland resilience across broad geographic scales to prioritize wetlands for management action (Webb et al., 2013). The MARS indices complement numerical modeling approaches (reviewed by Fagherazzi et al., 2012) by assessing current environmental conditions relevant to SLR resilience using empirical data, rather than making spatial or temporal predictions and testing different scenarios.

The MARS indices currently incorporate ten metrics related directly to both sensitivity and exposure to SLR. Scoring is based on explicit thresholds, and the indices assess different aspects of resilience. These indices can easily be adapted by other users. Calculation of the indices from the metrics is transparent in our approach and can be altered, for instance to allow for weighting of metrics of particular importance in some types of marshes. Likewise, scoring thresholds for existing metrics can be altered to better reflect relevant conditions in other regions; as new sites apply the indices, the thresholds can be refined. To facilitate expanded application of the MARS indices, we therefore also include a spreadsheet template and calculation tool that can be adapted and modified by new users (Table A3).

The scope of the MARS indices could also be broadened in the future through addition of new metrics. Marshes are complex systems, affected by interactions between many abiotic and biotic factors (Day et al., 2008). Sensitivity to SLR is likely affected by exposure of marshes to other stressors, such as eutrophication, invasive species or herbivory; metrics could therefore be included that quantify such exposure to other stressors. A metric could also be included to assess dominance by C_3 vs. C_4 plants in the marshes, since the former may be able to increase productivity with increasing CO_2 concentrations associated with continued climate change (Curtis et al., 1989). A different category of metrics focusing on adaptive capacity to SLR could also be added. For instance, metrics could be developed to estimate migration potential using GIS-based quantifications of the percent of the marsh perimeter that has barriers to migration. Another metric could focus on socioeconomic measures, such as funding level or community support for marsh restoration in the region. Although we focused on SLR as the aspect of projected climate change most likely to have the single greatest effect on tidal marshes, future indices could also be developed to include other aspects such as temperature and precipitation (Osland et al., 2016).

The indices we have developed thus set the stage for development of richer future assessments, or evaluations tailored to particular regions or questions. Multi-metric indices have proliferated as management tools for benthic aquatic habitats, and are recognized as playing an important role in coastal decision-making (Diaz et al., 2004; Pinto et al., 2009). Our analysis represents a first “proof-of-concept” demonstration of the feasibility and utility of such indices for coastal wetlands.

4.2. Contrasts among metrics and indices

The five categories of metrics we included in our analysis address different aspects of marsh resilience to SLR. The color-coded synthesis of metric scores (Table 3) highlights our finding that most metrics are not significantly correlated with each other; the table shows a mix of colors for the metrics with no clear associations. At the level of individual marshes, there was also little consistency across categories – most marshes scored high on some and low on others. This is ecologically reasonable: for instance, a marsh such as Elkhorn Slough CA has a high tidal range, which gives it one type of resilience to SLR, but has vegetation that is near the bottom of its tolerance to inundation, which makes it vulnerable. Such contrasts among categories do not represent errors, but rather reveal the need for a holistic approach that integrates these different components of resilience.

Within our five categories, there were two pairs of correlated metrics: long-term SLR and short-term variability in water levels show very similar patterns across sites, as do long and short-term accretion rates. It was to avoid “double-counting” that these similar metrics were averaged into broader categories for the risk and average indices. However, within one category, marsh elevation distribution, the three metrics assessing whether existing marsh vegetation is low in the tidal frame revealed very different patterns (Table 3; Fig. 2). This demonstrates that marsh resilience to SLR cannot be universally estimated and compared among marshes using a single metric based on marsh elevations; instead, a multi-metric approach is needed to gauge resilience over broad spatial scales due to differences in plant community composition and flooding tolerance.

While inclusion of multiple metrics is important, it is possible that some metrics are more important contributors to marsh resilience than others. For this initial assessment, we have not weighted metrics differentially when calculating the indices to avoid arbitrary assignments of weights. However, future indices could certainly incorporate such weighting. For instance, the marsh elevation change rate seems very directly related to marsh resilience, while turbidity as a proxy for sediment supply may be less so, since degrading marshes sometimes generate high turbidity (Ganju et al*.*, 2015). One could therefore weight marsh elevation change more heavily than turbidity.

The three indices we used to calculate overall scores for marsh resilience also differed in the perspective they provided. Only the marsh at Tijuana River CA received the same score (as represented by the same shading in Table 3) on all three indices. Marshes at five other reserves received fairly similar scores: Hudson River NY scored high on all three; Grand Bay MS and North Inlet-Winyah Bay SC scored moderately on all three, and Waquoit Bay MA and Narragansett Bay RI consistently scored low. However, scores were less consistent at the other marshes. The least consistent marshes were ACE Basin SC and Elkhorn Slough CA, which each received a very high and very low score on one index. In both of these cases, the low score is from the MARS ratio index, which certainly provides important perspective on marsh resilience (Cahoon & Guntenspergen, 2010). However, because these marshes also have other attributes that increase resilience, such as high turbidity at ACE and low long-term exposure to SLR at Elkhorn Slough, they receive higher scores on the other integrative indices.

Given that the choice of index affects the outcome so drastically in some cases, it seems clear that the most thorough understanding of resilience comes from an assessment that includes multiple indices. This has been the consensus in application of integrative indices for estuarine habitat quality based on invertebrate communities: there is no single universal index, and the best assessment is obtained by employing multiple indices (Pinto et al., 2009).

4.3. National characterization of marsh resilience

The importance of comparative assessments of marsh resilience at a broad geographic scale has been widely recognized, as has been their dependence on coordinated monitoring networks (Cahoon & Guntenspergen, 2010; Webb et al., 2013). The NERRS invests heavily in place-based, coordinated monitoring, and serves as an ideal platform for such an assessment (NERRS, 2012; Buskey et al., 2015). Here we include 16 individual marshes widely distributed across 13 U.S. states to provide a snapshot of national resilience. Inclusion of more sites in the assessment would increase its scope as a tool for understanding broad trends across the continent as well as within particular regions. This should be feasible in the future given that many other organizations (e.g., National Park Service, U.S. Fish and Wildlife Service, U.S. Geological Survey) are collecting the necessary data, and that the NERR Sentinel Sites program continues to grow and will add new sites over time.

Overall, the average of the MARS indices across all 16 marshes reveals moderate resilience by U.S. marshes to SLR. This is a somewhat less optimistic assessment than a recent meta-analysis of selected marshes throughout the U.S. and Europe (Kirwan et al., 2016), perhaps because our assessment was limited to assessment of marshes in their current footprints, and did not include marsh migration potential. In any case, our approaches differed: Kirwan et al. (2016) modeled changes under different SLR and sediment concentration scenarios, while our study assessed the relative resilience of different marshes based on current environmental conditions. The exact MARS scores for these marshes should not be taken as definitive, but as an initial characterization that can be updated periodically as longer-term monitoring data are acquired. Long-term datasets that can integrate across periods of drought and flooding, or different oceanographic phases, provide more robust values than shorter-term monitoring, particularly for SET measurements of marsh elevation change and accretion measurements at marker horizons (Cahoon et al., 2011). The NERRS is committed to repeating this assessment at regular intervals, and the results will become increasingly reliable and more comprehensive with time.

4.4. Regional signatures of resilience

Overall, the MARS indices showed some patterns across regions; for instance, the Acadian and Californian regions scored highest on all indices (Fig. 4). There certainly were also strong contrasts among marshes within regions (Table 3), in part because we included a variety of tidal marsh types – for example, the marsh assessed in Chesapeake Bay MD is a tidal freshwater system, while that in Chesapeake Bay VA is a saltwater system. Nevertheless, our multivariate analysis of all ten metrics combined (Fig. 5) revealed strong regional groupings due to shared values for particular metrics, with especially strong separation between the Pacific and Virginian regions. An earlier multivariate analysis (Apple et al., 2008) of NERR water quality data using principal components analysis also generally grouped reserves with others in their biogeographic region, with separation of regions driven primarily by differences in temperature and salinity, with salinity being a strong predictor of nitrogen loading.

The single metric that displayed the clearest regional patterns (Table 3) was short-term variability in water levels, with unusually high water levels in the Acadian and Virginian regions (Sallenger et al., 2012), moderate levels in the Carolinian and Louisianan, and generally low levels on the Pacific Coast (Bromirski et al., 2011). The percentage of marsh vegetation below MHW also shows a clear regional pattern: the entire Pacific Coast has a low percentage of vegetation below MHW. This pattern can be attributed to taxonomic differences in marsh dominance on the Pacific vs. Atlantic and Gulf Coasts; many Pacific marshes are dominated by *Salicornia pacifica*, which cannot tolerate as much inundation as *Spartina* spp. (Wasson et al., 2013; Janousek et al. 2016). On the Atlantic Coast, variable patterns emerged for this metric. At marshes in Waquoit Bay and Narragansett Bay, the high percentage of vegetation below MHW is likely the consequence of recent rapid SLR (Sallenger et al., 2012). Future assessments with more replication of different marsh types could be stratified by factors such as salinity regime, dominant marsh species, or marsh elevation, which would allow for more robust detection of regional patterns and more consistent comparisons of marshes within a category.

4.5. Local variation in marsh resilience

Most reserves participating in this analysis supplied data for a single marsh ecosystem. For small, relatively homogenous estuaries such as Tijuana River CA, the geographic scope of the assessment consisted of much of the marsh in the estuary. At the other extreme, reserves on small portions of very large estuaries, such as San Francisco and Chesapeake bays, submitted data from a single marsh within a large, heterogeneous estuary. To explore variability in marsh resilience within an estuary, we examined multiple marshes within three reserves. In each of these cases, there were some contrasts among marshes within a system, both for individual metrics and for MARS indices (Table 4). These contrasts were most pronounced at Hudson River, where nearby marshes were subject to different hydrological regimes and harbored different plant communities. Nevertheless, within the scope of the larger analysis, the variation within estuaries was considerably lower than that among estuaries.

The relatively low within-estuary variability observed at Elkhorn Slough and Narragansett Bay (Table 4) suggests that at least some of the scores for the marshes in Table 3 are probably good estimates for the larger systems surrounding them, when these are fairly homogenous. However, the moderate variability observed within Hudson River estuary (Table 4) suggests that the exact scores provided in Table 3 should not necessarily be taken as representative for heterogeneous estuaries. The three Hudson River marshes, despite close proximity, differed in dominant plant species, which affected elevational distributions and sedimentation rates. One cannot assume processes are uniform across wetlands, but rather must obtain site-specific data (Webb et al., 2013). Physical and biological differences in marsh attributes can affect their rates of elevation change and responses (Cahoon, 2006). Thus, while MARS indices can be fruitfully applied at any spatial scale, care must be taken to extrapolate to a sufficiently homogenous area surrounding the site of data collection.

4.6. Applying MARS indices to management and policy

There is increasing recognition of the need to develop and implement climate adaptation strategies to help valued ecosystems and the communities they support prepare for and cope with climate change (Stein et al., 2013). For coastal wetlands, systematically collected data from coordinated networks covering a large geographic scale can play an instrumental role in shaping regional and national policy, including coastal planning, adaptation, and mitigation strategies (Webb et al., 2013). There is a key “early warning” function of monitoring coastal wetlands that serve as “sentinel sites”, allowing flexible climate adaptation strategies to be developed and adopted (Callaway et al., 2007). Our analysis of marsh resilience to SLR at 16 NERR tidal marshes serves as one such early warning, potentially informing the development of management strategies by providing timely information on the relative resilience of different marshes.

Climate adaptation strategies for coastal wetlands include enhancing resilience of the existing marsh plain and facilitating desired transformations such as removing barriers to upland migration of marshes or creating new marshes through sediment addition (Wigand et al., 2016). Which strategy should be adopted depends on an understanding of the level of resilience that a tidal marsh is likely to have in the face of SLR. The MARS indices we developed allow coastal managers to choose the most appropriate strategy for a particular tidal marsh system. Below, we illustrate how management strategies can ideally be tailored to MARS index scores, recognizing that in practice management decisions can be complex and are influenced by multiple factors.

For marshes that score consistently high on the MARS indices, the management focus should be on preservation. These marshes are likely to survive for at least a century, and so the most important investment is in their conservation and protection from other stressors. Examples of management actions for these high-scoring marshes include increasing conservation status (e.g., purchasing high resilience marshes that are not yet in conservation ownership) and helping to support marsh function by decreasing polluted run-off to the marsh, removing invasive species, or restoring top predators that help to control herbivores.

For marshes that have moderate scores, or a mix of scores on the MARS indices, coastal managers should consider taking action to enhance resilience to SLR, increasing the likelihood that these marshes can persist into the future. For instance, waterlogging can sometimes be reduced by improving drainage, thin layers of sediment can be added to increase marsh elevation, creating fringing oyster reefs can facilitate sediment accretion, or upstream dams can be removed to enhance sediment supply (Wigand et al., 2016). Enhancing freshwater inputs may also increase the rate of organic soil formation, increasing marsh resilience (Day et al., 2008).

For marshes that scored consistently low on the MARS indices, very different management approaches may be required. These marshes are unlikely to survive the next century of projected SLR in their current location. The best long-term investment in these areas may be to facilitate desired transformations. Low-lying uplands projected to be at a suitable elevation to sustain tidal marsh migration can be acquired as conservation land so that new marshes in these sites can replace the ones that have drowned (Callaway et al., 2007; Wigand et al., 2016). New, more resilient marshes also can be created within the existing tidal marsh footprint, for instance through sediment addition projects to create higher marshes. Of course, facilitating desired transformations such as marsh migration and creation of new marshes may also be important strategies to increase future marsh extent for systems with more resilient marshes, but for those sites with very low resilience, they appear to be the only reasonable strategies.

In summary, these integrative indices of marsh resilience are novel tools that coastal managers can apply to help select appropriate climate adaptation and management strategies for coastal wetlands in the face of rising seas. One certainty that applies to all tidal marshes is the need for continued long-term monitoring and study, both to understand how these important ecosystems respond to SLR and other stressors associated with climate change and to evaluate the management actions implemented to protect them.

Acknowledgements

We are grateful to Nina Garfield, Whit Saumweber, Erica Seiden, and Marie Bundy for championing the NERR Sentinel Sites program for the past decade. Philippe Hensel and Artara Johnson provided instrumental support for establishing NERRS vertical control networks. Support and data collection were provided to individual reserves by H. Baden, T. Buck, D. Burdick, N. Burnett, D. Cahoon, K. Callahan, J. Callaway, J. Carey, L. Carroll, M. Cordrey, C. Cornu, A. Deck, A. Demeo, S. Denham, W. Doar, D. Durant, C. Endris, J. Fear, S. Findlay, J. Goins, T. Gregory, J. Hamilton, G. Hood, J. Leffler, Maryland DNR-Resource Assessment Service, C. Nieder, J. McIlwain, M. Mensinger, C. Mitchell, W. Reay, J. Schmitt, V. Sheremet, D. Siok, P. Stacey, R. Stevens, B. Toothman, W. Underwood, S. Upchurch, U.S. Geological Survey in Woods Hole MA, E. Van Dyke, E. Watson, R. Weber, H. Wells, C. Whiteman, M. Woodrey, and J. Zedler. We are grateful to two reviewers who provided thoughtful, extensive comments that improved the manuscript. Funding was provided by many state partner organizations and by NOAA's Office for Coastal Management.

References

Apple JK, Smith EM, Boyd TJ (2008) Temperature, salinity, nutrients, and the covariation of bacterial production and chlorophyll-a in estuarine ecosystems. Journal of Coastal Research, **SI (55)**, 59–75.

Bromirski PD, Miller AJ, Flick RE et al. (2011) Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. Journal of Geophysical Research: Oceans, **116**, C7.

Buskey EJ, Bundy M, Ferner M et al. (2015) Chapter 21: System-Wide Monitoring Program of the National Estuarine Research Reserve System: Research and Monitoring to Address Coastal Management Issues. In: *Coastal Ocean Observing Systems* (eds Yonggang L, Kerkering H, Weisberg RH), pp. 392-415, Academic Press, New York.

Cahoon DR (2006) A review of major storm impacts on coastal wetland elevations. Estuaries and Coasts, **29**, 889-898.

Cahoon DR, Guntenspergen GR (2010) Climate change, sea-level rise, and coastal wetlands. National Wetlands Newsletter, **32**, 8-12.

Cahoon DR, Perez BC, Segura BD et al. (2011) Elevation trends and shrink-swell response of wetland soils to flooding and drying. Estuarine, Coastal and Shelf Science, **91**, 463-474.

Callaway JC, Parker VT, Vasey MC et al. (2007) Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change. Madroño, **54**, 234-248.

Clarke KR, Gorley RN, Somerfield PJ et al. (2014) Change in marine communities: an approach to statistical analyses and interpretation, 3rd edition. Primer-E, Plymouth.

Craft C, Clough J, Ehman J et al. (2009) Forecasting the effects of accelerated sea level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment, **7**, 73-78.

Curtis PS, Drake BG, Leadley W et al. (1989) Growth and senescence in plant communities exposed to elevated CO_2 concentrations on an estuarine marsh. Oecologia, **78**, 20-26.

Day JW, Christian RR, Boesch DM et al. (2008) Consequences of climate change on the ecogeomorphology of coastal wetlands. Estuaries and Coasts, **31**, 477-491.

Deegan LA, Johnson DS, Warren RS et al. (2012) Coastal eutrophication as a driver of salt marsh loss. Nature, **490**, 388-394.

Diaz RJ, Solan M, Valente RM (2004) A review of approaches for classifying benthic habitats and evaluating habitat quality. Journal of Environmental Management, **73**, 165-181.

Fagherazzi S, Kirwan ML, Mudd SM et al. (2012) Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. Reviews of Geophysics, **50**, RG1002.

Ganju NK, Kirwan ML, Dickhudt PJ et al. (2015) Sediment transport-based metrics of wetland stability. Geophysical Research Letters, **42**, 7992-8000.

Gedan KB, Silliman BR, Bertness MD (2009) Centuries of human-driven changes in salt marsh ecosystems. Annual Review of Marine Science, **1**, 117-141.

Grayson RB, Finlayson BL, Gippel CJ et al. (1996) The potential of field turbidity measurements for the computation of total phosphorus and suspended solids loads. Journal of Environmental Management, **47**, 257-267.

Gunderson LH (2000) Ecological resilience-in theory and application. Annual Review of Ecology and Systematics, **31**, 425-439.

Hansen J, Sato M, Hearty P et al. (2016) Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2^{o}C global warming could be dangerous. Atmospheric Chemistry and Physics, **16**, 3761-812.

Holdredge C, Bertness MD, Altieri AH (2009) Role of crab herbivory in die-off of New England salt marshes. Conservation Biology, **23**, 672-679.

Holling CS (1973) Resilience and stability of ecological systems. Annual review of ecology and systematics, **4**, 1-23.

Janousek CN, Buffington KJ, Thorne KM et al. (2016) Potential effects of sea-level rise on plant productivity: species-specific responses in northeast Pacific tidal marshes. Marine Ecology Progress Series, **21**, 548:111-25.

Kirwan ML, Guntenspergen GR, D'Alpaos A et al. (2010) Limits on the adaptability of coastal marshes to rising sea level. Geophysical Research Letters, **37**, L23401.

Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature, **504**, 53-60.

Kirwan ML, Temmerman S, Skeehan EE et al. (2016) Overestimation of marsh vulnerability to sea level rise. Nature Climate Change, **6**, 253-260.

Lefor MW, Kennard WC, Civco DL (1987) Relationships of salt-marsh plant distributions to tidal levels in Connecticut, USA. Environmental Management, **11**, 61-68.

Mcleod E, Chmura GL, Bouillon S et al. (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Frontiers in Ecology and the Environment, **9**, 552-560.

Miller F, Osbahr H, Boyd E et al. (2010) Resilience and vulnerability: complementary or conflicting concepts? Ecology and Society **15**, 11.

Miller KM, Mitchell BR, McGill BJ (2016) Constructing multimetric indices and testing ability of landscape metrics to assess condition of freshwater wetlands in the Northeastern US. Ecological Indicators, **66**, 143-52.

Morris JT, Porter D, Neet M et al. (2005) Integrating LIDAR elevation data, multi-spectral imagery and neural network modelling for marsh characterization. International Journal of Remote Sensing, **26**, 5221–5234.

Morris JT, Sundareshwar PV, Nietch CT et al. (2002) Responses of coastal wetlands to rising sea level. Ecology, **83**, 2869-2877.

National Estuarine Research Reserve System (NERRS) (2012) Sentinel Sites program guidance for climate change impacts. NERRS final program guidance. 24 pp.

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science, **328**, 1517-1520.

Osland MJ, Enwright NM, Day RH et al. (2016). Beyond just sea-level rise: considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. Global Change Biology, **22**, 1-11.

Packman JJ, Comings KJ, Booth DB (1999) Using turbidity to determine total suspended solids in urbanizing streams in the Puget Lowlands. In: *Confronting Uncertainty: Managing Change in Water Resources and the Environment* (Canadian Water Resources Association annual meeting, Vancouver, BC, 27-29 October 1999), pp. 158-165.

Pinto R, Patrício J, Baeta A et al. (2009) Review and evaluation of estuarine biotic indices to assess benthic condition. Ecological Indicators, **9**, 1-25.

Rahmstorf S (2010) A new view on sea level rise. Nature Reports Climate Change, **1004**, 44-5.

Redfield AC (1972) Development of a New England Salt marsh. Ecological Monographs, **42**, 201-237.

Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea level rise on the Atlantic coast of North America. Nature Climate Change, **2**, 884–888.

Schile LM, Calloway JC, Morris JT et al. (2014) Modeling tidal marsh distribution with sea-level rise: evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. PLoS ONE, **9(2)**, e88760.

Schoolmaster DR, Grace JB, William Schweiger E (2012) A general theory of multimetric indices and their properties. Methods in Ecology and Evolution, **3**, 773-781.

Silliman BR, van de Koppel J, Bertness MD et al. (2005) Drought, snails, and large-scale die-off of southern U.S. salt marshes. Science, **310**, 1803-1806.

Stein BA, Staudt A, Cross MS et al. (2013) Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Frontiers in Ecology and the Environment, **11**, 502-510.

Wasson K, Woolfolk A, Fresquez C. (2013) Ecotones as indicators of changing environmental conditions: rapid migration of salt marsh-upland boundaries. Estuaries and Coasts, **36**, 654-664.

Watson EB, Oczkowski AJ, Wigand C et al. (2014) Nutrient enrichment and precipitation changes do not enhance resiliency of salt marshes to sea level rise in the northeastern U.S. Climatic Change, **125**, 501-509.

Webb EL, Friess DA, Krauss KW et al. (2013) A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise. Nature Climate Change, **3**, 458-465.

Wigand C, Ardito T, Chaffee C et al. (2016) A climate change adaptation strategy for management of coastal marsh systems. Estuaries and Coasts, DOI 10.1007/s12237-015-0003-y (in press).

828 Table 1. Marsh resilience categories and metrics used in this study, including data needs for each metric.

Category	Metric	Data needs
Marsh elevation distributions	Percent of marsh below MHW	Frequency distribution of marsh elevations Estimate of mean high water
	Percent of marsh in lowest third of plant distribution	Frequency distribution of marsh elevations
	Skewness	Frequency distribution of marsh elevations
Marsh elevation change	Elevation change rate (mm yr^{-1})	Time-series data from surface elevation tables (SETs)
Sediment/accretion	Short-term accretion rate (mm yr^{-1})	Time-series data from marker horizons
	Long-term accretion rate (mm yr^{-1})	Soil cores for radiometric dating
	Turbidity (NTU)	Mean turbidity from water quality sondes
Tidal range	Tidal range (m)	Mean daily tidal range from water quality sondes
Sea-level rise	Long-term rate of SLR (mm yr^{-1})	Long-term data from NWLON station
	Short-term inter-annual variability in water levels (mm)	Inter-annual variability data from NWLON station

Table 2. Numeric thresholds and color codes for individual metrics and all categories and indices. For metric scoring, red = 1, brown = 2, yellow = 3, light green = 4, and dark green = 5. Note that even though we did not use TSS in our study, scoring thresholds for this metric are also presented because it can be used in lieu of turbidity in future assessments.

Metric thresholds	Percent of marsh below MHW	> 80%	> 60%	> 40%	> 20%	≤ 20%
	Percent of marsh in lowest third of plant distribution	> 80%	> 60%	> 40%	> 20%	≤ 20%
	Skewness	> 1.5	> 0.5	0.5 to -0.5	< -0.5	< -1.5
	Elevation change rate (mm yr^{-1})	≤ 2	> 2	> 3	> 4	> 5
	Short-term accretion rate (mm yr^{-1})	≤ 2	> 2	> 3	> 4	> 5
	Long-term accretion rate (mm yr^{-1})	≤ 2	> 2	> 3	> 4	> 5
	Turbidity (NTU) / Total suspended solids (mg l^{-1})	≤ 10	> 10	> 20	> 30	> 40
	Tidal range (m)	≤ 0.6	> 0.6	> 1.2	> 1.8	> 2.4
	Long-term rate of SLR (mm yr^{-1})	> 3.4	> 2.6	> 1.8	> 1	≤ 1
	Short-term inter-annual variability in water levels (mm)	> 25	> 15	> 5	5 to -5	< -5
Scoring	All metrics	1	2	3	4	5
	All categories	< 2	< 3	< 4	< 5	5
	MARS - risk	0-1	2	3	4	5
	MARS - average	1	> 1	> 2	> 3	> 4
	MARS - ratio	< -0.5	> -0.5	> 1.5	> 2.5	> 3.5

Table 3. Metrics (raw data), categories (mean scores among all metrics within each category), and MARS index scores for the 16 primary marshes in this study, which are identified by NERR name but in some cases represent subsections within a NERR. For regions, ACA=Acadian, VIR=Virginian, CAR=Carolinian, LOU=Louisianan, COL=Columbian, and CAL=Californian. To illustrate scoring, all data are color coded using the scheme shown in Table 2.

		ACA	VIR						CAR			LOU	COL		CAL		
		NH	MA	RI	NY	DE	MD	VA	NC	SC	SC	MS	WA	OR	CA	CA	CA
		Great Bay	Waquoit Bay	Narragansett Bay	Hudson River	Delaware	Chesapeake Bay	Chesapeake Bay	North Carolina	NI-WB	ACE Basin	Grand Bay	Padilla Bay	South Slough	San Francisco Bay	Elkhorn Slough	Tijuana River
Metrics	Percent of marsh below MHW	42	62	61	38	0	16	27	84	58	47	53	0	34	25	40	1.5
	Percent of marsh in lowest third	8.9	14	5.6	38	57	17	7.9	10	26	44	3.8	85	4.0	7.0	52	54
	Skewness	-1.6	1.5	-0.13	-0.50	-1.6	-1.3	-0.32	-0.22	-0.11	0.07	1.2	2.1	-1.3	-1.5	0.97	0.62
	Elevation change (mm yr^{-1})	4.3	1.7	1.8	13.5	4.1	2.5	5.3	-1.9	2.6	2.0	4.2	n/a	-0.20	3.8	0.53	6.1
	Short-term accretion (mm yr^{-1})	2.7	n/a	1.8	12.7	6.1	31	8.3	n/a	n/a	n/a	1.4	n/a	1.4	3.1	3.3	5.4
	Long-term accretion (mm yr^{-1})	n/a	n/a	2.8	6.0	7.2	4.2	n/a	n/a	2.7	n/a	n/a	4.5	1.6	3.9	3.8	n/a
	Turbidity (NTU)	34	1.8	4.5	23	49	24	5.1	18	17	25	22	6.7	14	61	23	12
	Tidal range (m)	2.7	0.55	0.53	1.4	1.3	0.74	0.76	1.2	1.4	1.8	0.42	2.5	1.8	1.3	1.6	1.0
	Long-term SLR rate (mm yr^{-1})	1.8	2.8	2.7	2.8	3.4	3.7	4.6	2.1	3.2	3.2	3.2	1.1	0.84	1.9	1.2	2.1
	Short-term SLR variability (mm)	n/a	23	18	28	22	30	21	-0.50	-2.1	-2.1	-1.5	-2.6	-7.1	-15	-5.8	-0.92
Categories	Marsh elevations	4.3	3.0	3.3	3.7	4.3	4.7	4.0	3.0	3.3	3.0	3.3	2.3	4.3	4.3	3.0	3.3
	Elevation change	4	1	1	5	4	2	5	1	2	1	4	n/a	1	3	1	5
	Sediment/accretion	3.0	1.0	1.3	4.3	5.0	4.0	3.0	2.0	2.0	3.0	1.5	2.5	1.3	3.7	3.0	3.5
	Tidal range	5	1	1	3	3	2	2	2	3	4	1	5	4	3	3	2
	Sea-level rise	4.0	2.0	2.0	1.5	1.5	1.0	1.5	3.5	3.0	3.0	3.0	4.0	5.0	4.0	4.5	3.5
Indices	MARS - risk	5	1	1	4	4	2	3	2	3	4	3	2	3	5	4	4
	MARS - average	4.1	1.6	1.7	3.5	3.6	2.7	3.1	2.3	2.7	2.8	2.6	3.5	3.1	3.6	2.9	3.5
	MARS - ratio	2.4	0.60	0.66	4.8	1.2	0.67	1.1	-0.9	0.83	0.63	1.3	n/a	-0.24	2.0	0.5	2.9

Table 4. Within-NERR variability in marsh resilience at the Narragansett Bay RI, Hudson River NY, and Elkhorn Slough CA NERRs. For clarity, all data are color coded using the scheme shown in Table 2.

		Narragansett Bay		Hudson River			Elkhorn Slough	
		Coggeshall	Nag	Outer Tivoli North	Inner Tivoli North	Tivoli South Bay	Upper Slough	Lower Slough
Metrics	Percent of marsh below MHW	86	61	38	81	95	40	7.1
	Percent of marsh in lowest third	18	5.6	38	19	81	52	36
	Skewness	0.75	-0.13	-0.50	-1.0	1.7	1.0	0.50
	Elevation change (mm yr^{-1})	1.2	1.8	14	4.1	13	0.53	1.2
	Short-term accretion (mm yr^{-1})	2.2	1.8	13	18	20	3.3	4.0
	Long-term accretion (mm yr^{-1})	n/a	2.8	6.0	6.0	8.0	3.8	3.4
	Turbidity (NTU)	6.9	4.5	23	23	26	23	15
	Tidal range (m)	1.2	0.53	1.4	1.4	1.5	1.6	1.6
	Long-term SLR rate (mm yr^{-1})	2.7	2.7	2.8	2.8	2.8	1.2	1.2
	Short-term SLR variability (mm)	18	18	28	28	28	-5.8	-5.8
Categories	Marsh elevations	2.7	3.3	3.7	3.3	1.0	3.0	4.0
	Elevation change	1	1	5	4	5	1	1
	Sediment/accretion	1.5	1.3	4.3	4.3	4.3	3.0	2.7
	Tidal range	2	1	3	3	3	3	3
	Sea-level rise	2.0	2.0	1.5	1.5	1.5	4.5	4.5
Indices	MARS - risk	0	1	4	4	3	4	3
	MARS - average	1.8	1.7	3.5	3.2	3.0	2.9	3.0
	MARS - ratio	0.43	0.66	4.8	1.4	4.4	0.5	1.1

Short captions for Supplemental figures and tables

Figure A1: nMDS with additional marsh sites.

Table A1: Metadata and characteristics of each study marsh.

Table A2: Metadata for sampling procedures.

Table A3: Tool for conducting MARS assessment at new sites. (Excel file)

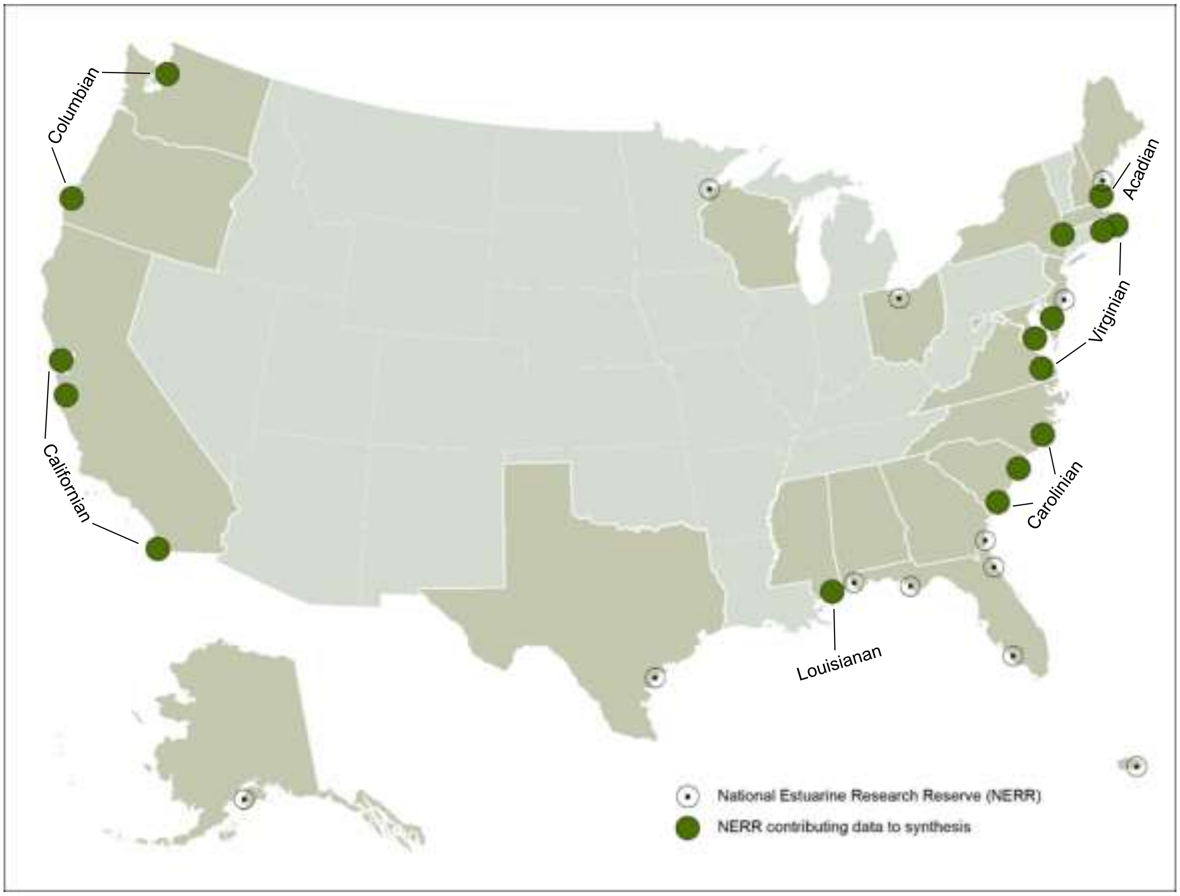

Figure 1. Map of the National Estuarine Research Reserve System showing the 16 reserves participating in this study. Bounds of NERR biogeographic regions are also shown.

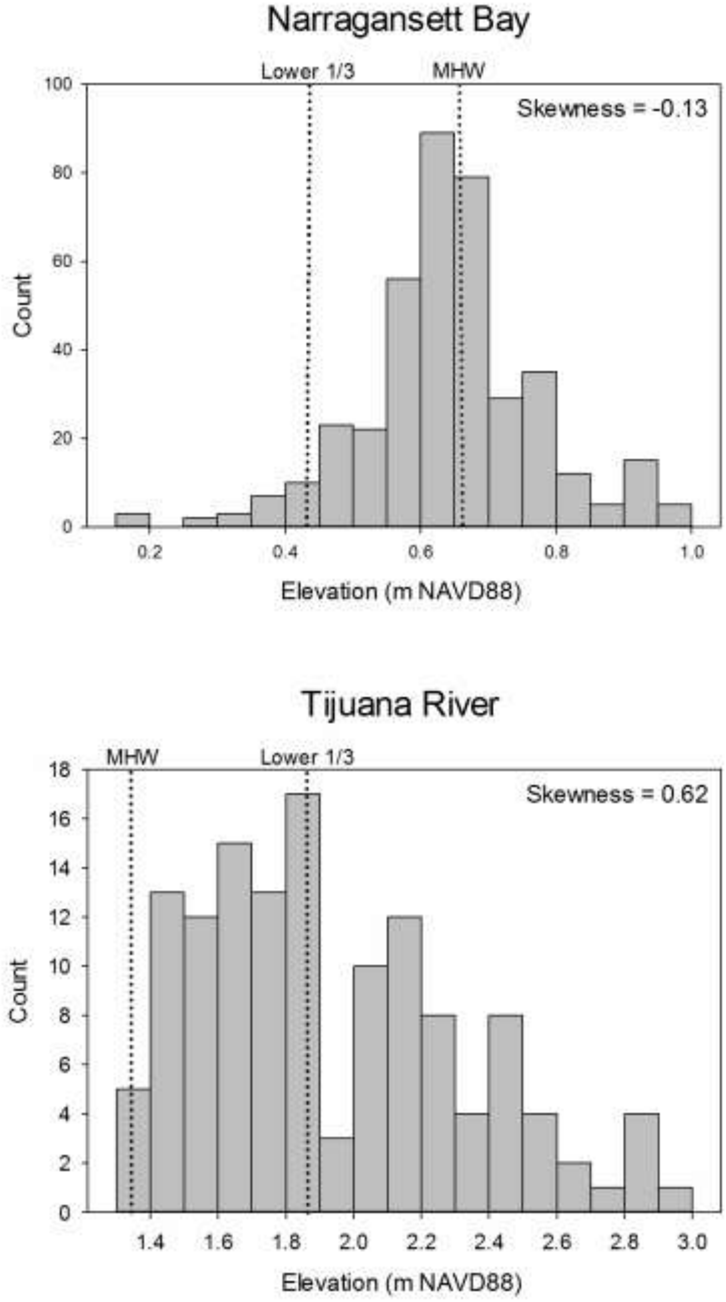

Figure 2. Comparison of three marsh elevation metrics. The frequency of different elevations observed in transects across the marsh at Narragansett Bay and Tijuana River NERRS are shown in the bar graphs. The elevations of MHW and the lower third of plant distribution range are also shown as dotted lines, and the calculated skew of the data is shown in the upper right. A substantial portion falls below MHW but not in the lower third of vegetation distribution at Narragansett, while the reverse is true at Tijuana, illustrating that different metrics can yield different indications of resilience.

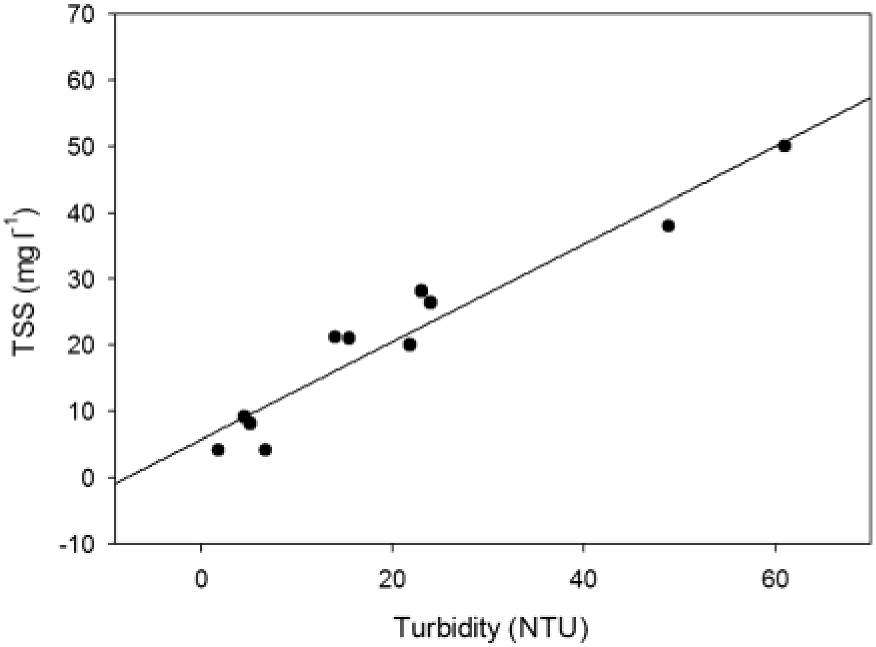

Figure 3. Relationship between total suspended solids (TSS) and turbidity at the site level. Relationship is highly significant based on a linear regression ($R^2 = 0.93$; $p < 0.0001$; n = 11 sites).

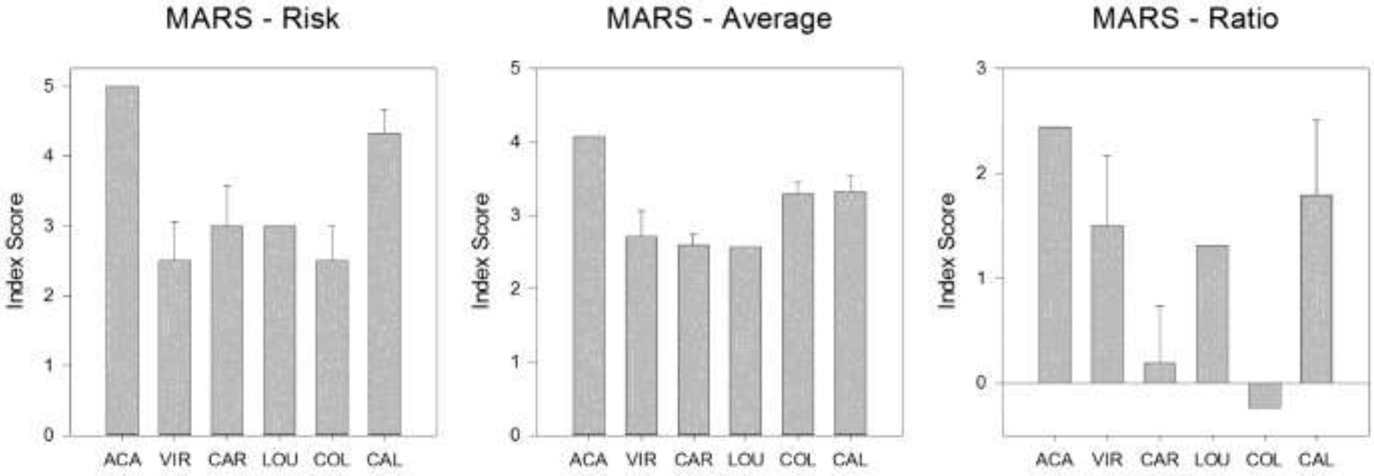

Figure 4. Patterns in mean index scores among biogeographic regions. Bars are means across all marshes within each region; error bars are 1 SE. For regions, ACA=Acadian, VIR=Virginian, CAR=Carolinian, LOU=Louisianan, COL=Columbian, and CAL=Californian.

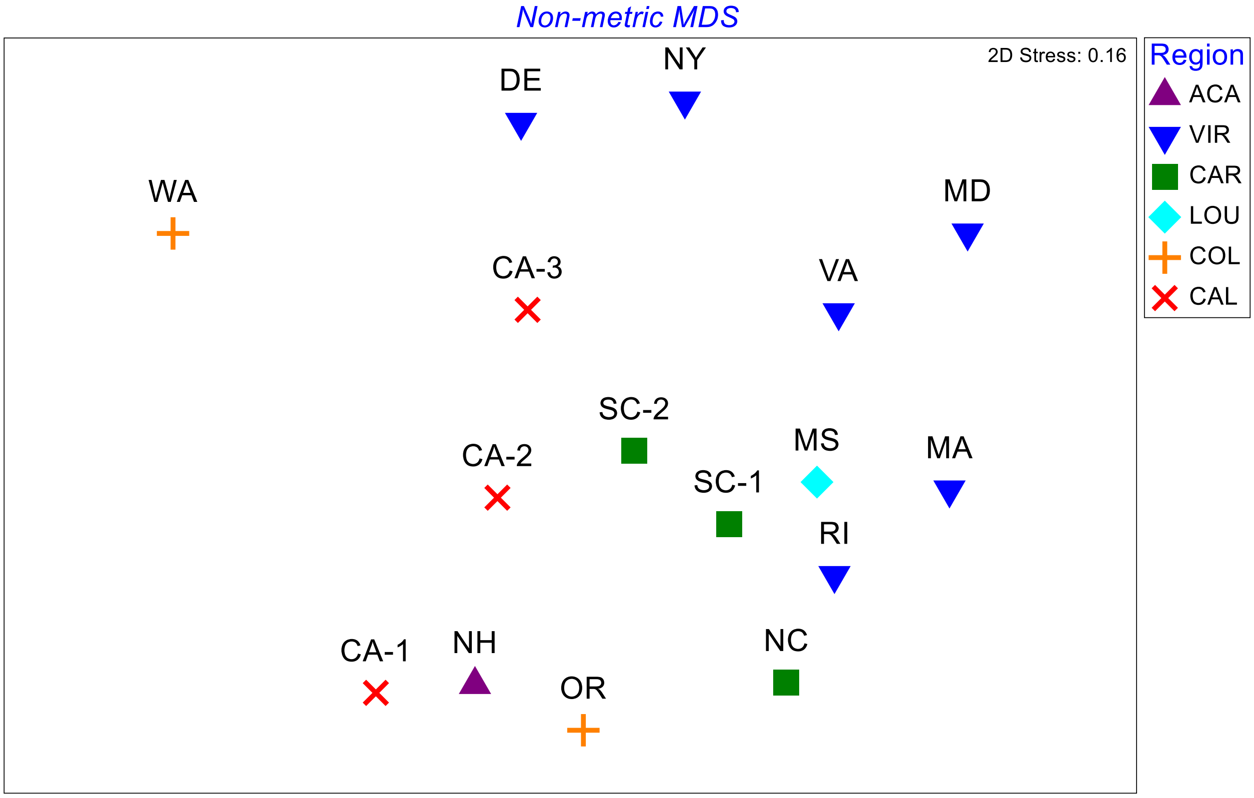

Figure 5. Non-metric multidimensional scaling plot showing similarities among the 16 NERR marshes based on marsh resilience metrics included in this study. Regions are coded as in Fig. 4. Marshes are labelled with state codes; for states with multiple sites, SC-1=North Inlet-Winyah Bay NERR, SC-2=ACE Basin NERR, CA-1=San Francisco NERR, CA-2=Elkhorn Slough NERR, and CA-3=Tijuana River NERR. The two freshwater marshes are in New York (NY) and Maryland (MD).